Folds and Faults in Pennsylvania Anthracite-Beds.

BY BENJAMIN SMITH LYMAN, PHILADELPHIA, PA.

(Atlanta Meeting, October, 1895.)

It has seemed that it might be a highly useful contribution to the study of structural geology to assemble, in as compact a form and on as large a scale as practicable, a great number of cross-sections of actual workings in the Pennsylvania anthracite beds. Accordingly the accompanying thirty-three page-plates, containing 177 sections, have been prepared from the numerous very valuable cross-section sheets of the State Geological Survey, besides a key-map, to show where the sections were made.

The sections are all in northwesterly and southeasterly directions, and are looked at from the southwest. They are drawn with equal horizontal and vertical scales, and are consequently not misleading, as distorted ones would almost necessarily be. They have been reduced by photography from the original scale of 400 feet to the inch to one of 500 feet to the inch, except a couple of them on much larger scales. Initial letters and numbers on each section refer to the section and sheet of the original Atlases of the Northern, Eastern Middle, Western Middle, and Southern anthracite-fields. The geographical position of each section is also indicated by its distance and direction from the nearest large town. The portions of a bed worked out on the line of the sections are represented by two light lines, indicating the top and bottom of the bed; but where the space is filled with black, the position of the bed is well ascertained, and where there is less certainty, the bed is represented by a single light line.

An inspection and tabulation of the general forms of the principal and subordinate basins and saddles of the cross-sections, show that the law that the northwesterly dips are steeper than the southeasterly ones, is not by any means so universal as H. D. Rogers seems to say in his able discussion of the laws of geological structure in the State Geological Report of 1858. On page 889 of vol ii., he says:

"Almost invariably, those [the flexures] of a simply undulated tract exhibit their steeper slopes directed all to one quarter."

Again, page 814, he says;

"There exist among the undulations of the strata in Pennsylvania a few—they are very few—exceptions to the almost universal law of a superior degree of abruptness of incurvation upon the northwest slopes of the anticlinal waves. These abnormal instances of relative dip belong almost invariably to the secondary class of flexures, which I have never regarded as true waves pervading the earth's crust, but as comparatively superficial foldings occasioned by the joint agency of pulsation and lateral crumpling. There are a few examples of unusual steepness of the southeast dips in the primary class of flexures; but nearly every one of these exceptions applies to only a local portion of the wave, and will be found connected either with a fault in the strata, or with an oblique interference of the end of an anticlinal of another group, I think there does not exist within the whole wide undulated zone of the strata of the Appalachian chain generally, a wave or group of waves of the first order, which is abnormal as respects the direction of the flatter and steeper slopes, except where we can directly refer to the influence of some prodigious crust-dislocation. . . . . Of the lesser class of flexures of a reversed profile, we may instance many in the anthracite coal-fields, particularly in the Shamokin basin."

The cross-sections in our plates are obviously not selected, consciously or unconsciously, with any reference to the form of the basin, and might, so far as that is concerned, be considered as made quite at random, and as likely, therefore, to indicate in an unprejudiced way what may be the general laws of the forms of the basins and saddles. It is true that the number of the undulations is not large enough in some of the subdivisions of the anthracite-region to be considered a perfectly precise indication of the relative number of the different forms; but the result for the 177 sections in the whole region, with 500 saddles and basins, large and small—nearly half of them (219) large—may probably be accepted as giving some useful indications. Taking them all together, it appears that nearly half of them have about equal dips on the two sides, and about as large a number have steeper northwesterly dips, and one-third as many have steeper southeasterly dips; or more precisely, three-sevenths of the whole number have the two dips about equal; three-sevenths steeper northwesterly dips, and one-seventh steeper southeasterly dips; or 43 per cent., 42½ per cent. and 14½ per cent. respectively.

In order to ascertain what the corresponding proportions might be in the four different fields of the region, and in the smaller folds as distinguished from the larger ones, so far as the small number of sections could give indications, tables were made showing the number and percentages of the larger or main basins, and of the main saddles, and of the smaller or subordinate ones in each field, that have about equal dips on the two sides, or steeper northwesterly dips or steeper south-easterly ones. The division into main and subordinate folds may not in every instance be accurate, but probably is sufficiently exact for the purpose, or to correspond with the exactness of the comparison in other respects. In some cases, adjacent basins and saddles have a dip in common; but that also would probably not influence the main results. As might be expected, in each group, main or subordinate, the percentages of the different forms in the basins were about equal to those in the saddles; and very closely equal in the large number of cases supplied by the whole region, less closely, it is true, for the scantier cases of the different fields. It is only needful, then, to give here a single table of the percentages in the different fields, and in the two classes of main and subordinate folds (whether basins or saddles), as follows:

Percentages of Equal and Steeper Dips.

	Main Folds.			Subordinate Folds.		
	Equal Dips.	North Steep.	South Steep.	Equal Dips.	North Steep.	South Steep.
Northern Anthracite-field, .	58½	27¼	14¼	40½	38½	21
Eastern Middle " .	33½	53	13½	37¾	51½	10¾
Western Middle " .	45	43½	11½	71	20½	8½
Southern Middle " .	21	60	19	50	37½	12½
All, ...	37½	48	14½	48	38	14

The table shows that in the whole anthracite region only three-eighths of the larger folds are symmetrical, while about half of them have steeper northerly dips, and about one-seventh steeper southerly ones; but that about half of the smaller folds are symmetrical, three-eighths have steeper northerly dips, and one-seventh have steeper southerly ones. In the different fields, however, the results would seem plainly to be different. In the Northern anthracite-field, decidedly more than half of the larger folds are symmetrical, only about half as many have steeper northerly dips, and about a quarter as many have steeper southerly dips; while of the subordinate folds about two-fifths are symmetrical, a nearly equal number have steeper northerly dips, and half as many have steeper southerly dips. In the Eastern Middle field one-third of the larger folds are symmetrical, over half have steeper northerly dips, and about one-seventh have steeper southerly dips; but of the subordinate folds, three-eighths are symmetrical, one-half have steeper northerly dips, and one-ninth have steeper southerly ones. In the Western Middle field rather less than half of the larger folds are symmetrical, about an equal number have steeper northerly dips, and about one-ninth have steeper southerly ones; but of the subordinate folds nearly three-quarters are symmetrical, only one-fifth have steeper northerly dips, and one-twelfth have steeper southerly ones. Finally, in the Southern field, only about one-fifth of the larger folds are symmetrical, nearly two-thirds have steeper northerly dips, and about one-fifth have steeper southerly ones; but of the subordinate folds one-quarter are symmetrical, three-eighths have steeper northerly dips, and one-eighth steeper southerly ones.

Some at least of the variations in the different groups seem to be quite too decided to be due merely to an accidental deficiency in the number of cases. There seems to be a strong resemblance between the Eastern Middle field and the Southern one in the figures for the larger folds, though not for the smaller ones; and it is only in these fields that the steeper northerly dips of the larger folds are much more numerous than the symmetrical folds. The Eastern Middle field is the only one where the smaller folds have more northerly steep dips than symmetrical ones. The Northern field has a remarkable number of symmetrical larger folds; and the Western Middle field a very remarkable number of symmetrical smaller folds, and very few with steeper northerly dips. In each group the steeper southerly dips are about a quarter or a third of the steeper northerly ones, except rather more in the smaller folds of the Northern and Western Middle fields; or say between the extreme limits of about a fifth and a half of the steeper northerly dips. It is evident that the prevalence of unsymmetrical folds, the so-called "normal flexure," and of steep northerly dips is notably not so strong as was formerly supposed;

and that it is very strikingly not so in the smaller folds of the Western Middle field and the larger ones of the Northern field.

Mr. Bailey Willis, in his very ingenious, richly illustrated and valuable memoir on "the Mechanics of Appalachian Structure," appended to the Thirteenth Annual Report of the United States Geological Survey, concludes, with apparent reason, that the Appalachian folds were caused by the contraction through cooling of the interior of the earth, a contraction, in itself very widespread, but in its visible effects principally concentrated within comparatively narrow limits; that the folding took place mainly in the space where the sediments of the Paleozoic sea had accumulated in great thickness and had depressed the underlying support, undoubtedly plastic and yielding under so great a load, thereby forming a more or less decided trough filled with the Paleozoic rocks; and that the contraction pressed against the sides of the trough with force so irresistible as to crumple the rock-beds into folds. Of course, the contraction beneath the Appalachian region itself would be added to the much greater contraction of the wider spaces outside. He argues that the place of the fold is partly determined by the original inclination, or, as he calls it, the "initial dip" of the beds, as indicated by their varying thickness; and perhaps even seemingly slight irregularities of surface had still more influence on the place of the origin of folds than he claims. Besides, the Paleozoic rocks, by their very sinking, would in some small degree tend to crumple, and would probably originate folds, according, not merely to the composition, firmness and character of the beds and groups of beds, but to any unevenness there might be from previous erosion in the ancient floor, and to any lightening of the load from erosion of the more recent surface during the folding. He points out that as the pressure on the beds is mainly horizontal from the sides, folds depend on the existence of beds or groups of beds of firm or structural character, that is, coherent, stiff and strong enough ("competent," as he calls them) to transmit the pressure and to lift up the load of rock-beds above them; and he shows that the sidewise pressure would be resolved by any irregularity in the direction of the firm beds into forces partly parallel with them and partly radial to their curves; that the radial forces would always push from the concave side of the curve towards the convex side; and, moreover, that the increased downward-pressing weight of the further side of any fold raised would occasion the transmisssion of the force onwards, so as to raise other "consequent folds," as he calls them, beyond the original main fold. He shows also that the surface-length, or profile-length, "dip-length" as he calls it, of a fold, depends, in cases where the conditions are otherwise uniform, either on the stiffness of the structural group of beds or on the weight of superincumbent beds. In such cases, namely, the arch will, for a given load, necessarily be as long as the stiffness allows (that is, the curve of least resistance), and obviously cannot be longer. But the surface or profile-length of the curve of a bed of given stiffness will be inversely proportioned to the load (that is, sharper and shorter, the greater the load). He argues, too, perhaps not quite clearly, that his "consequent" folds would be shorter than the original ones, but the single experimental result he cites seems rather to prove the contrary. The two shorter folds therein indicated, though subsequent, are not "consequent," in the sense of being transmitted through the original fold; for they are between that fold and the applied force, and may be shorter for other reasons, such as some slight unevenness or lack of homogeneity in the layers, or the increased nearness of the point of resistance by reason of the downward pressure of the original fold.

The shorter measure, then, of decidedly subordinate folds, within any space so limited that the conditions otherwise (including the superincumbent load) must be practically uniform, would seem clearly to be due to the fact that only a subordinate group of beds of less total stiffness is concerned. Also, at certain points in folds where special pressure exists, equivalent in its effect to increased load, narrower, subordinate folds may arise in subordinate groups of weaker beds confined between stiffer beds above and below. As the subordinate folds arise from the transmission of the pressure through the adjoining main folds, there would seem necessarily (under otherwise uniform conditions) to be throughout their length equal profile (or dip) length between the main and subordinate ones. But that, in the case or a rising or sinking ("pitching") anticlinal, would cause the subordinate folds riding upon it to have their axes not horizontally parallel with the main axis; so that a subordinate fold would descend the flank of a sinking anticlinal. It has long been known that the subordinate folds riding upon a main one are not parallel to it. Lesley, for example, alluded to the fact in his *Manual of Coal and its Topography*, 1856, page 185, as follows: "The beds descend at all angles, even more than vertical, thrown over on their backs—snapped and the edges slipped past each other—crushed by small rolls running obliquely through the sides of the greater anticlinal, each one of which carries a dozen small ones on its back," etc. Materials are not at hand to prove conclusively that the obliqueness is in the direction and of the amount just now suggested, though in a certain case, partially worked out, it would seem to be so.

Every fault shown in the cross-sections (except N. A. F. IIA., B, the 4th on Plate VI.) is of the class called longitudinal faults, overlaps, or reversed faults, and appears to be the result of the extreme folding and overstraining of one of these subordinate folds, riding upon a northerly or a southerly dip in about an equal number of cases (17 northerly to 16 southerly). In 5 cases, to be sure, the faults occur very close to the bottom of main basins; but even there, apparently, the form is taken of subordinate basins and saddles, and the main ones are not inverted, but are virtually symmetrical or nearly so. In all the 31 cases where the dip of the faults is clear, it is overturned with one or two possible exceptions. The most decided exception seems to be that of Plate VI., N. A. F. IIA., B. In 24 cases out of the 31 the resulting overturned dip is southerly. The upthrow in every case is on the side towards which the fault dips, except in 1 case; and except possibly in 2 more, if the dip be not reckoned as reversed. The throw of the fault is up to the south in 24 cases out of 33. Of the 9 others the dip of the main fold is northerly in 5 cases, about an equal division. Of the 28 faults where the "stratigraphic throw" (that is, the shortest distance from a layer on one side of the fault to the same layer on the opposite side) can be somewhat closely measured, it varies from 10 feet to about 160 feet, and averages about 62 feet, and the displacement (of the two ends of a layer along the plane of the fault) in the same way varies, in 26 sections where it is pretty clear, from 20 feet up to perhaps 240 feet and averages about 72 feet.

As it is evident, then, that the faults arise from the folding of subordinate groups of beds between stiffer ones, the extent of the faults depends like that of the subordinate folds on the firmness of those subordinate groups, and cannot in the same region much exceed the limits observed in these numerous cases. That may serve as a practical guide of some value in regard to the possible extent of faults in the region. For it would plainly be absurd to imagine that faults exist of a size wholly disproportionate to these, say with a stratigraphic throw very much greater than any that has been observed in the whole region, or a displacement very far more extensive than has been observed anywhere there. For example, it would be wholly absurd to imagine a fault with a stratigraphic throw of 250 or 300 feet, such as would be necessary for identifying a coarse conglomerate with the Pottsville conglomerate (No. XII) instead of with the conglomerate that frequently occurs above the Mammoth coal-bed, after the manner pointed out in these *Transactions*, vol. xxi., p. 713, as occurring at a number of places, and particularly at one, half a dozen miles west of Tamaqua; where, however, the topography as well as ample natural and artificial geological exposures have independently fully disproved the old erroneous conjecture of a great fault. Such an isolated fault of gigantic size would in any case be an impossibility in the midst of a region where numerous observations show that the size of faults is limited to much smaller dimensions; for the extent of the faults depends on the stiffness and strength of the beds and the original weight of the overlying beds, and in these respects there is no essential difference within the small space of one limited region.

We may conclude, then, that steep northerly dips in the Pennsylvania anthracite-region are much less prevalent than was formerly supposed; that nearly half the basins and saddles are about symmetrical; and that nearly three-fourths of the subordinate ones are so in the Western Middle field; but that less than a quarter of the main ones are so in the Southern field. Again, that the subordinate folds throughout the region are confined to subordinate groups of beds of inferior firmness, and are not parallel to the main folds, but probably at uniform profile-distances from the main axes, so as to descend the flank of a sinking anticlinal. Further, that the faults are almost invariably longitudinal or reversed faults, occasioned by the overstraining of subordinate folds, and corresponding in three-fourths of the cases to an overturned southerly dip, with the upthrow to the south; that such broken subordinate folds, whether dipping southerly or northerly, ride in equal number on the northerly-dipping and southerly-dipping sides of the main folds; that the stratigraphic throw averages only about 62 feet, and never exceeds 160 feet; and that the displacement averages 72 feet, and never exceeds 240 feet.

PLATE I.

CROSS-SECTIONS
OF
FOLDS AND FAULTS
OF ACTUAL WORKINGS IN
ANTHRACITE BEDS,
COMPILED BY
BENJAMIN SMITH LYMAN
FROM THE
CROSS-SECTION SHEETS
OF THE
PENNSYLVANIA GEOLOGICAL SURVEY.
FEB., 1895

THE HORIZONTAL AND VERTICAL SCALE OF THE SECTIONS IS 500 FEET TO AN INCH, UNLESS OTHERWISE STATED.

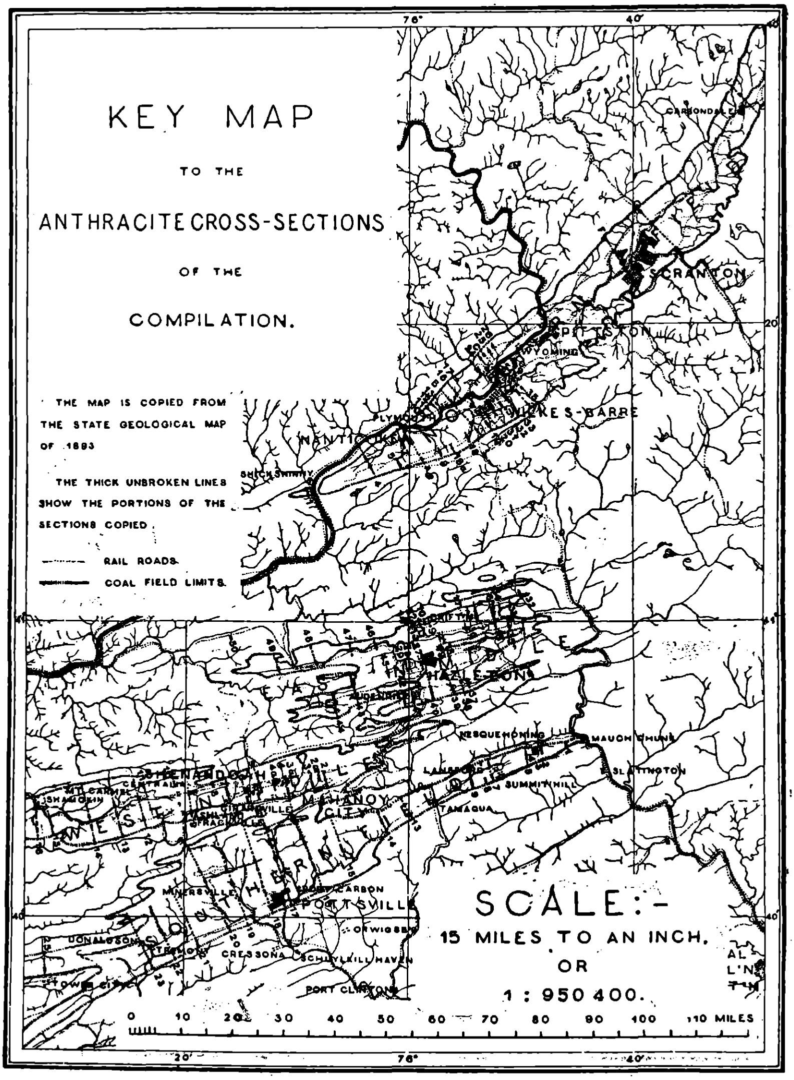
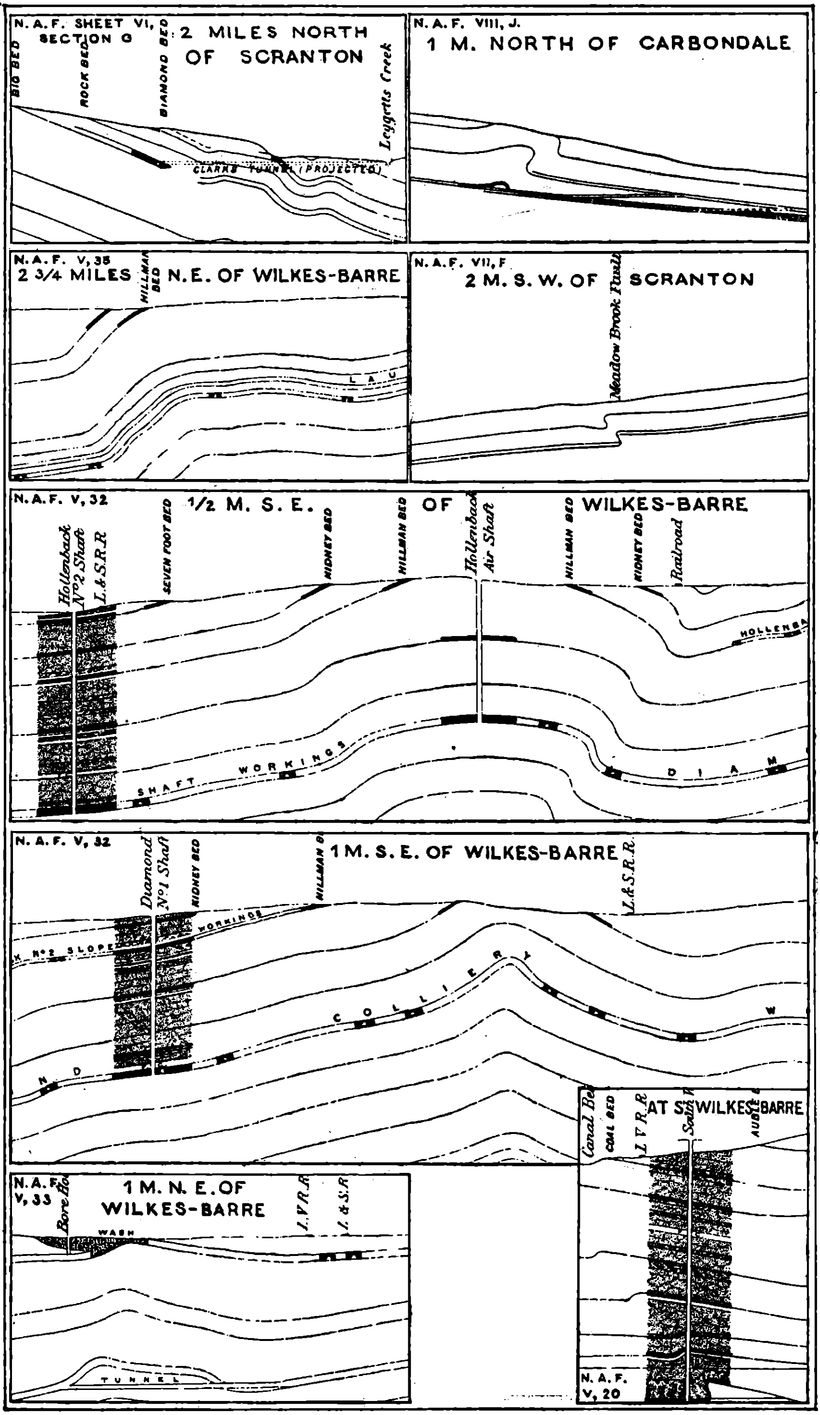


PLATE II.



Cross-Sections in the Anthracite-Region.

PLATE III.

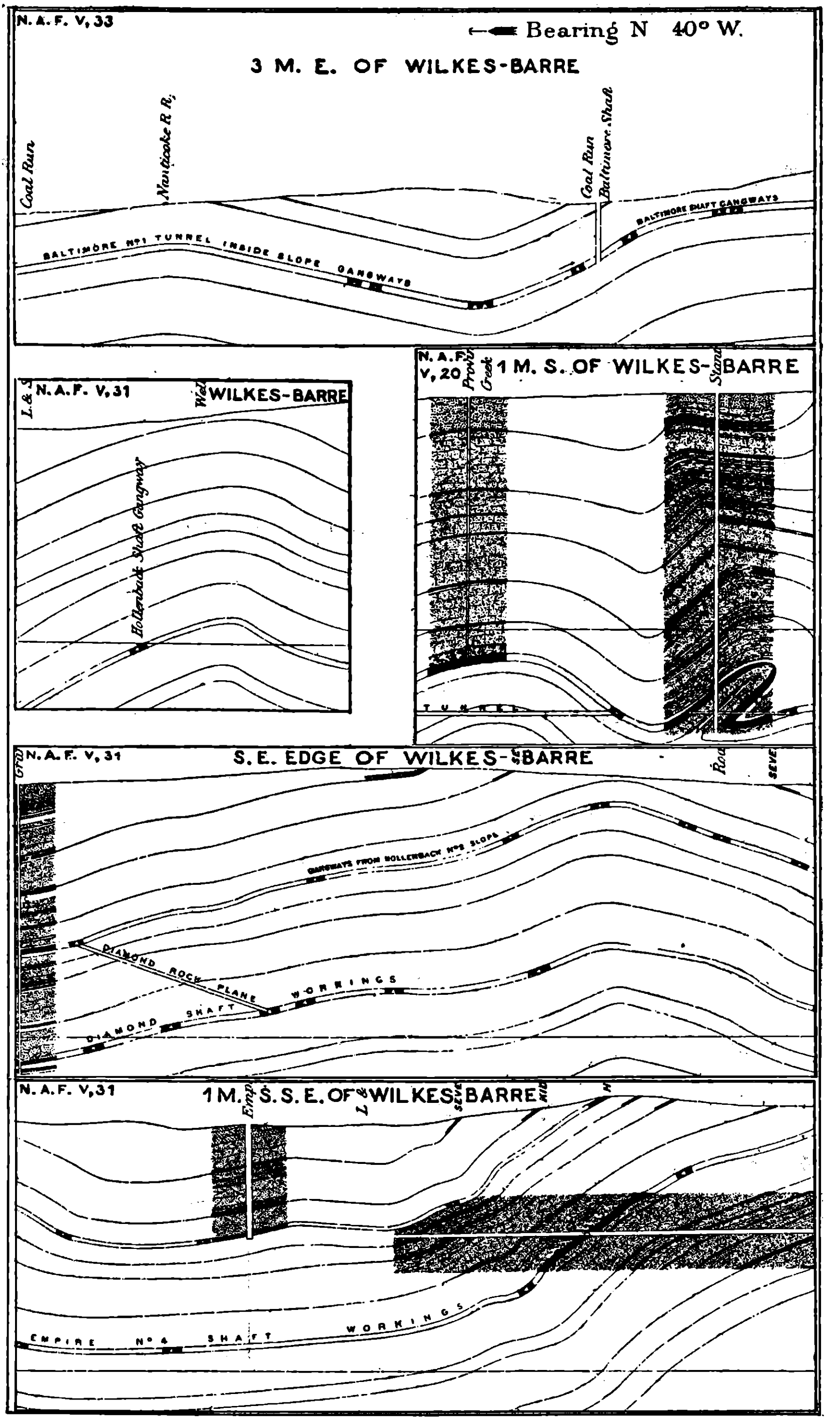


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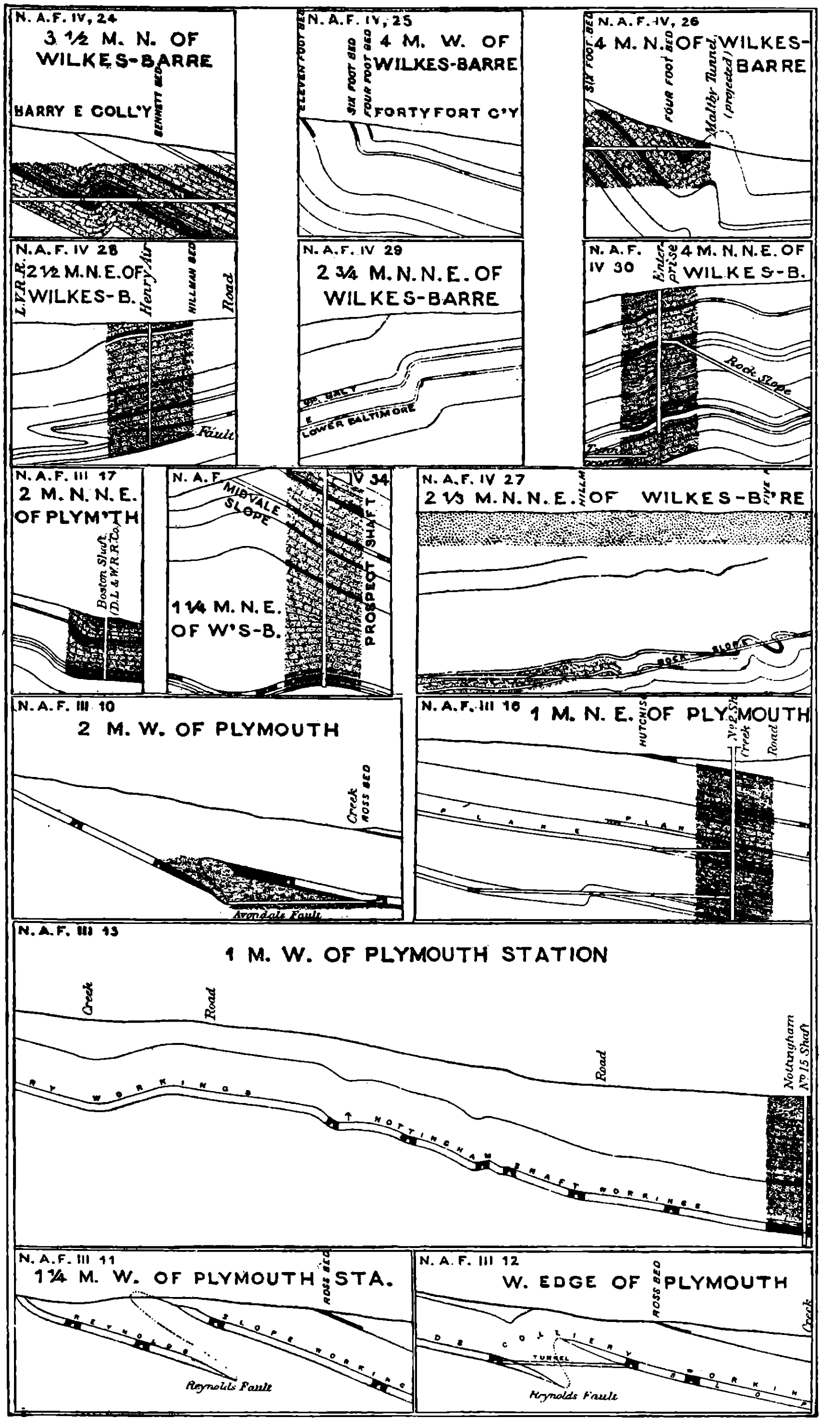
PLATE IV



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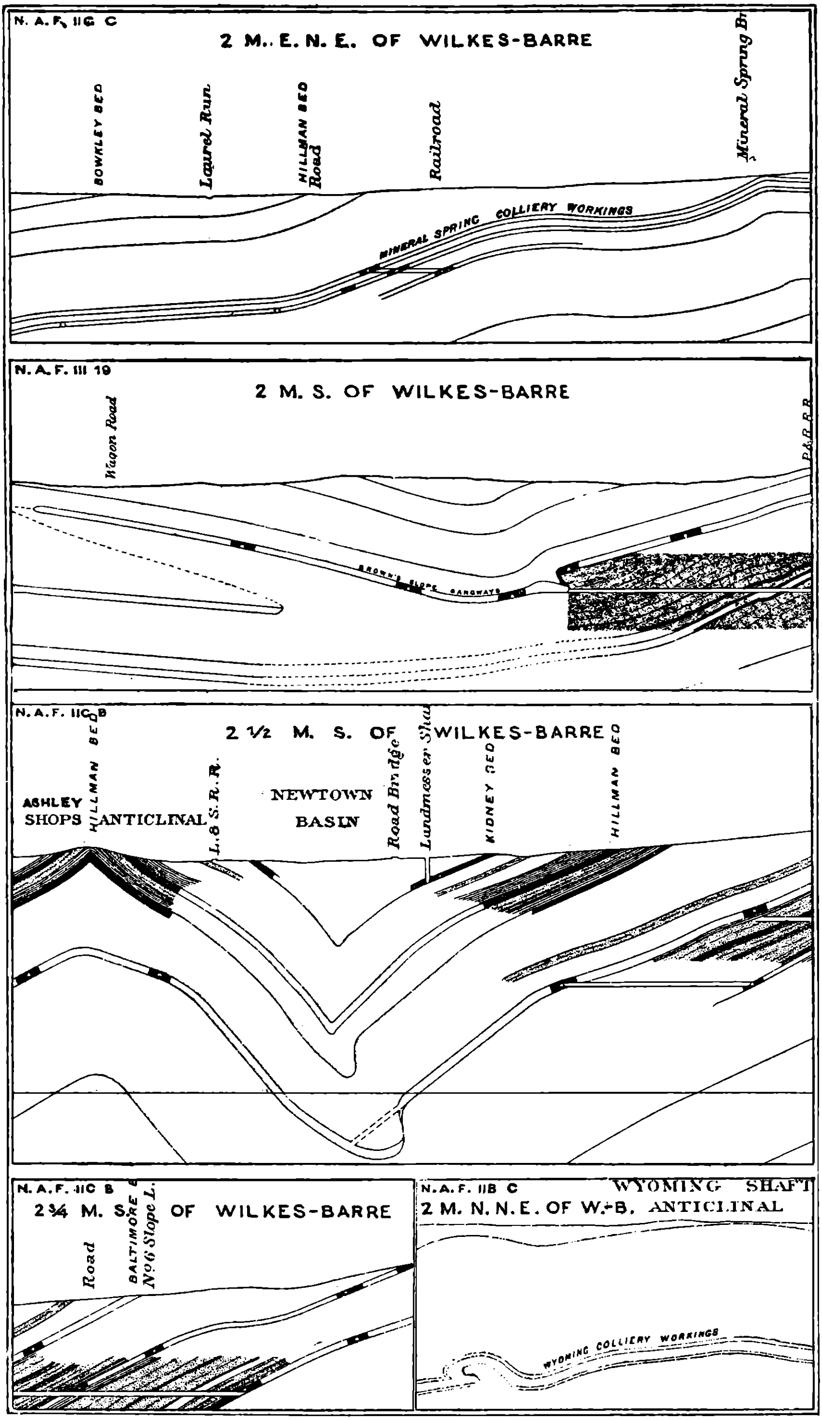

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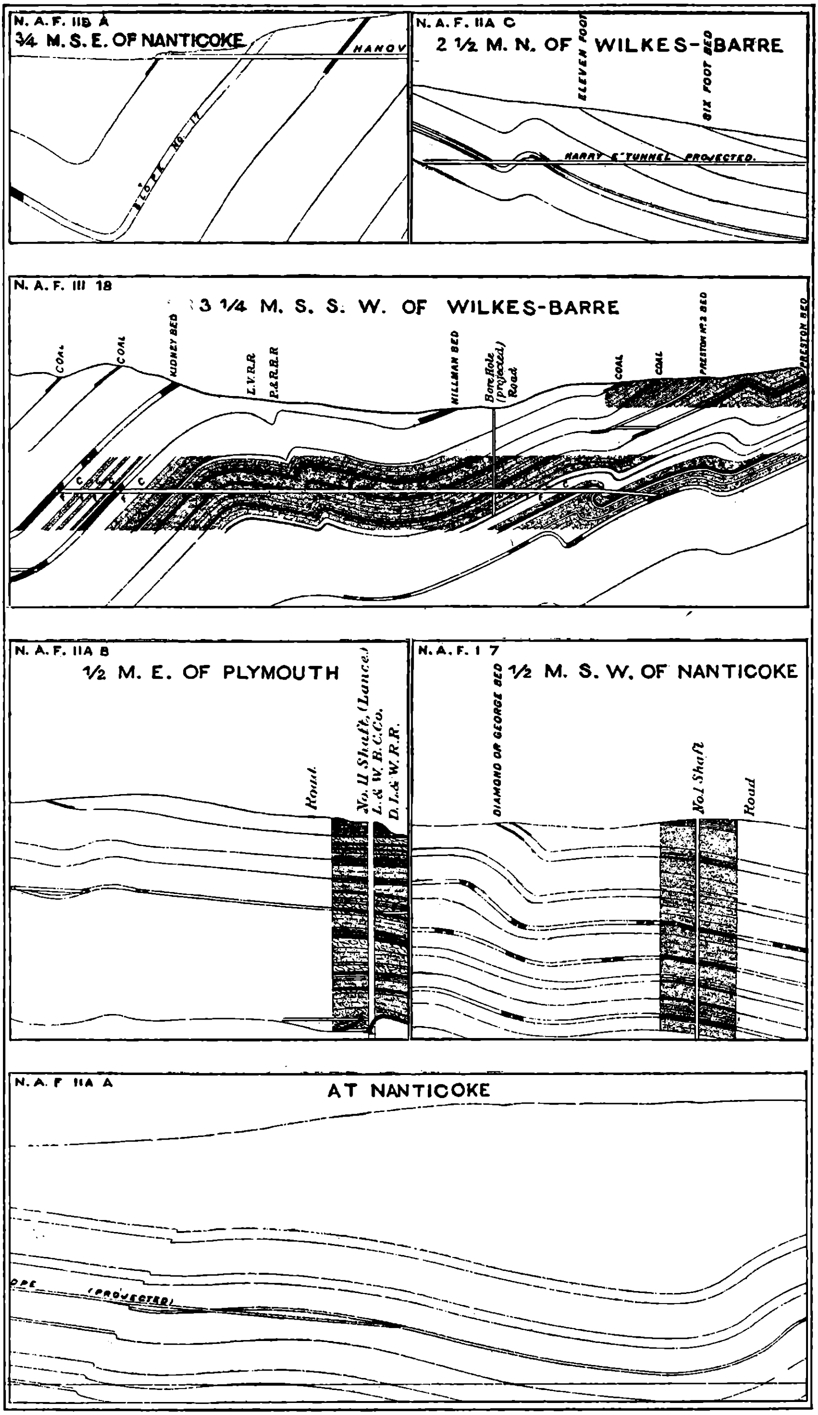
PLATE VI.



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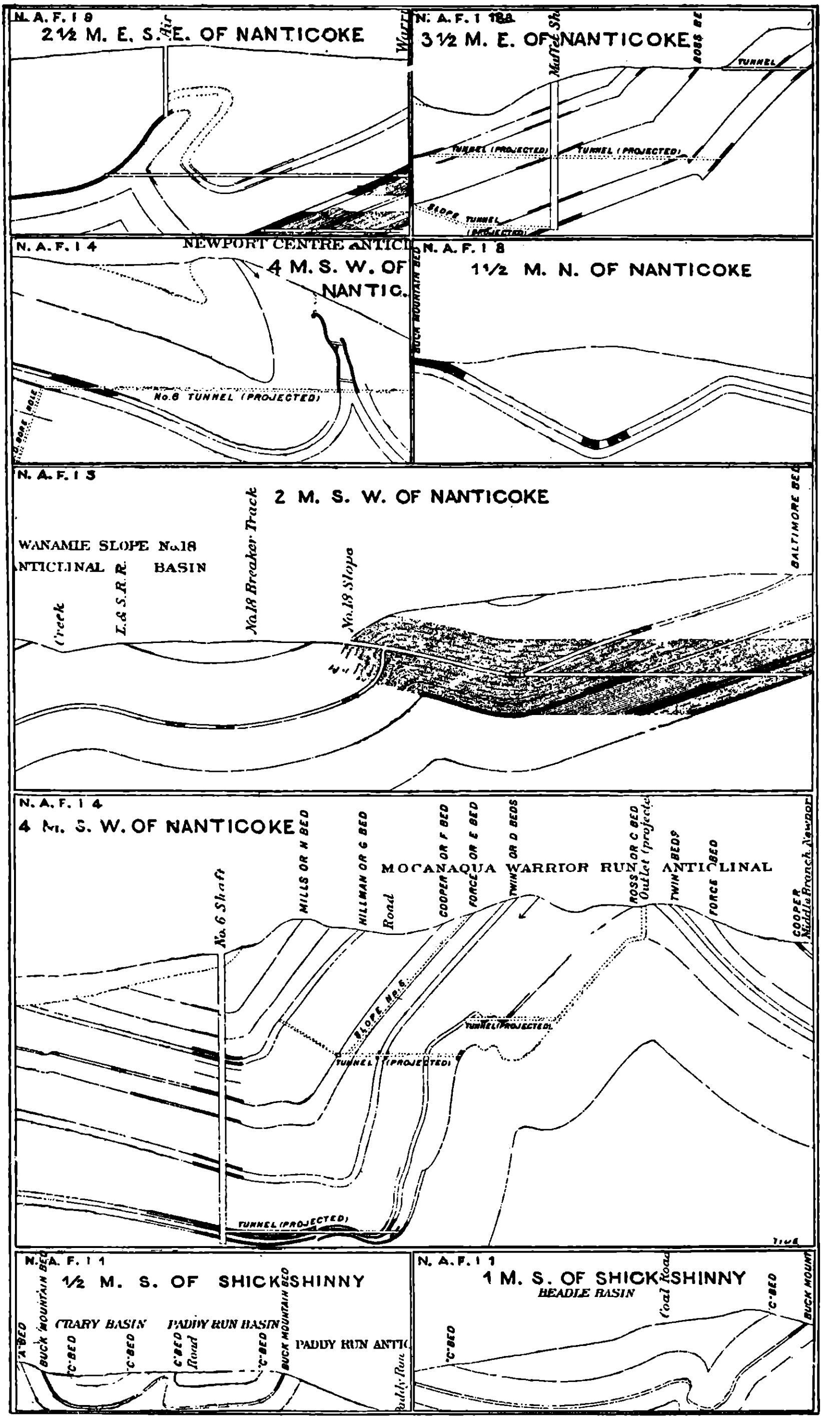

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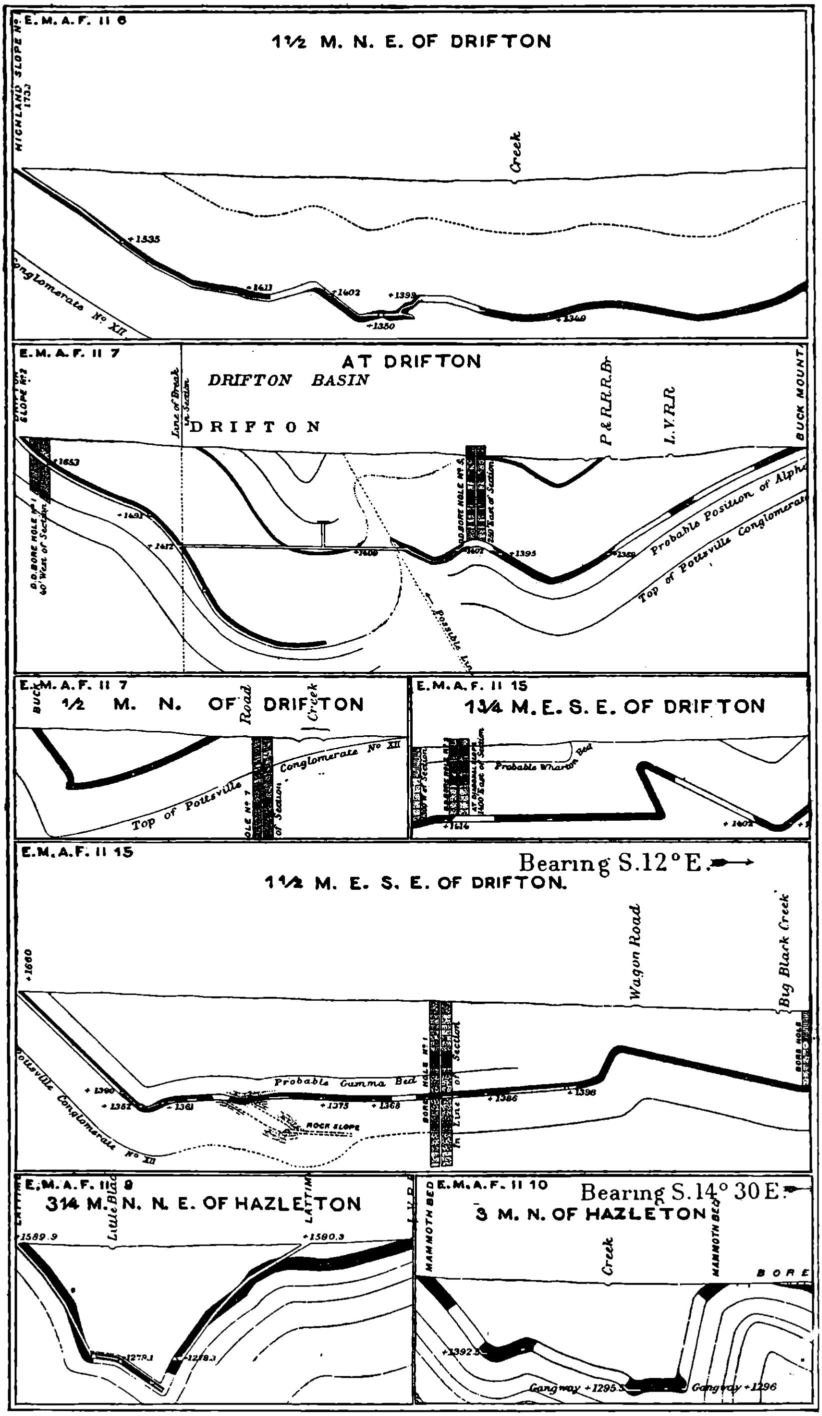
PLATE VIII.



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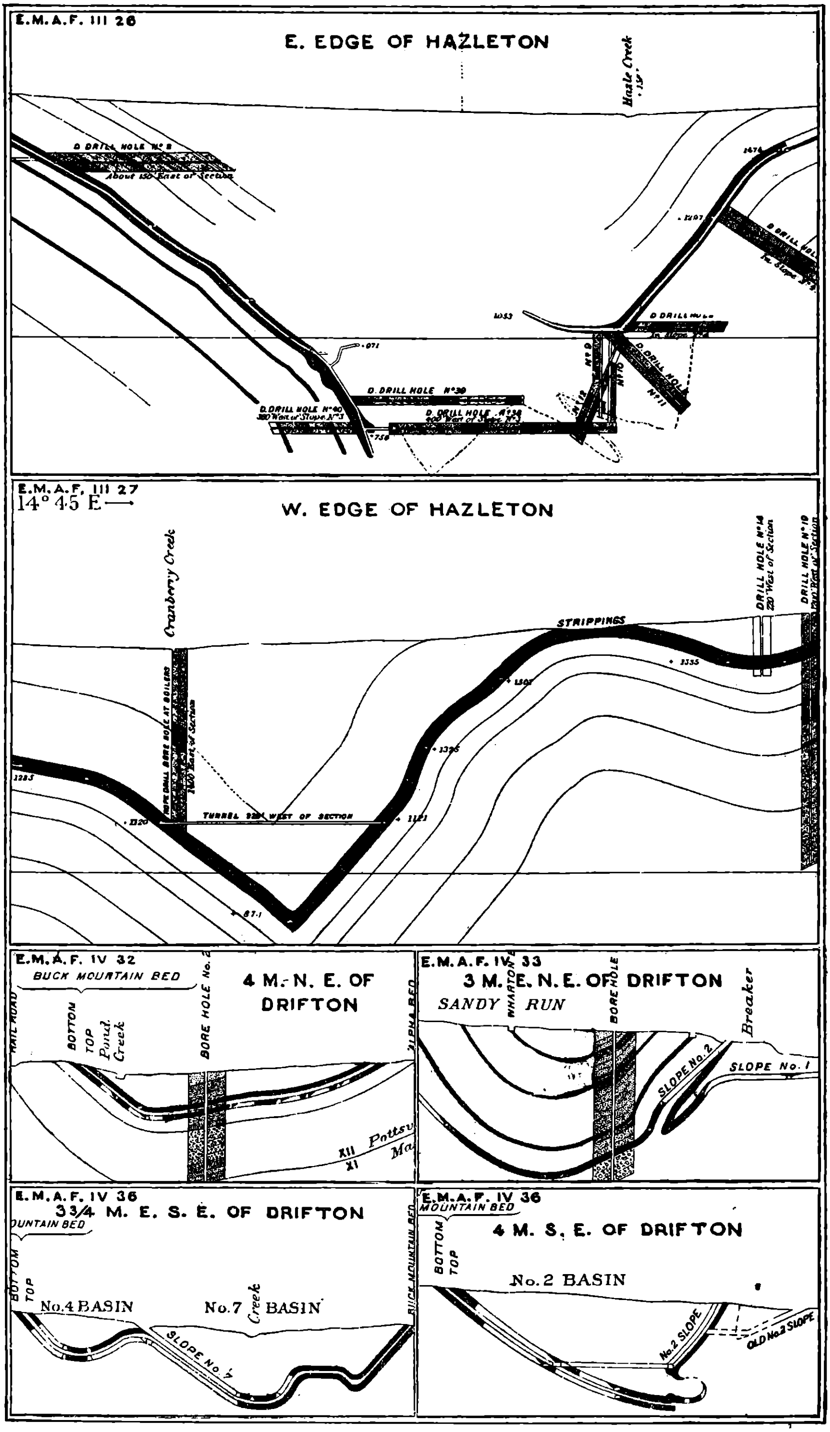

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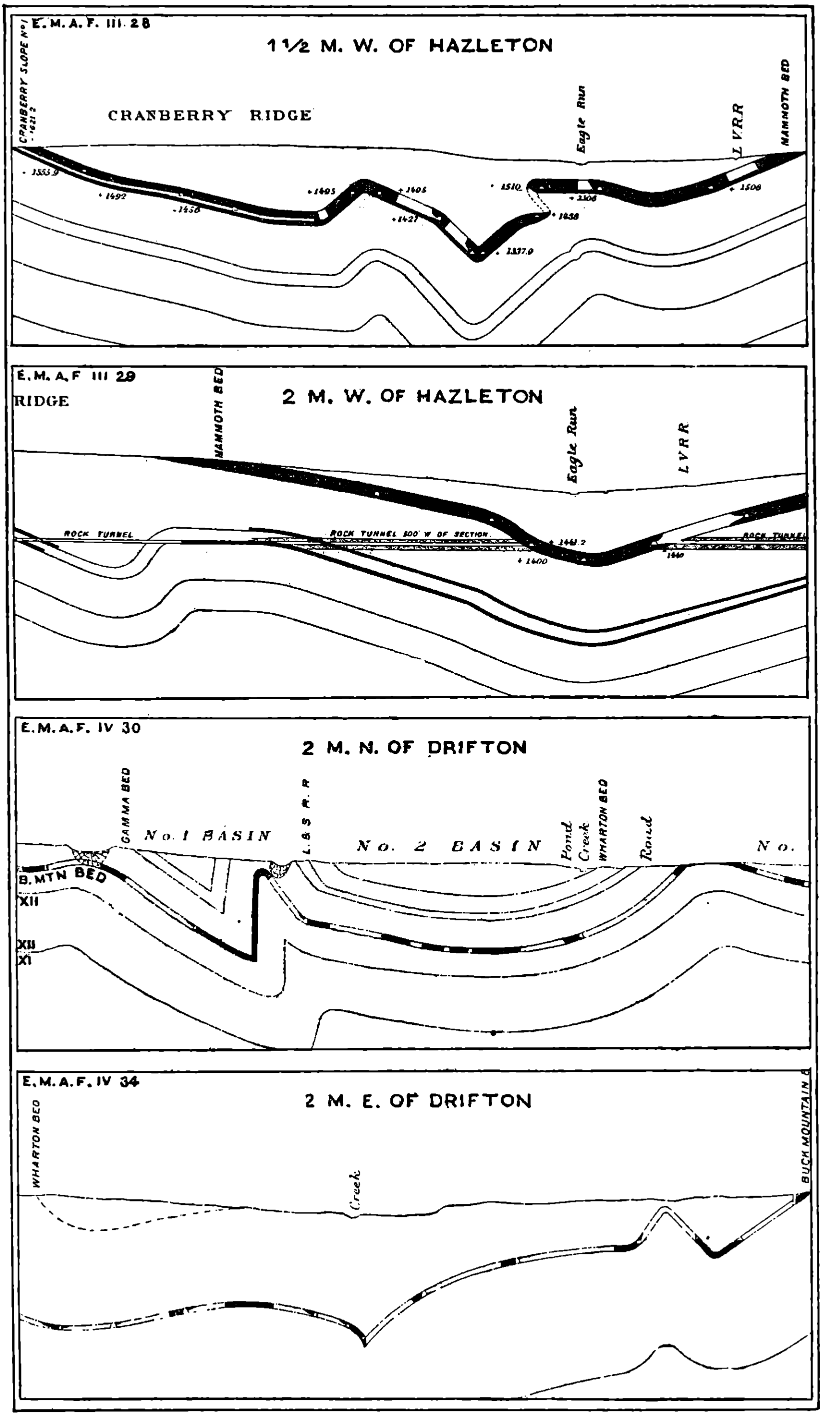
PLATE X.



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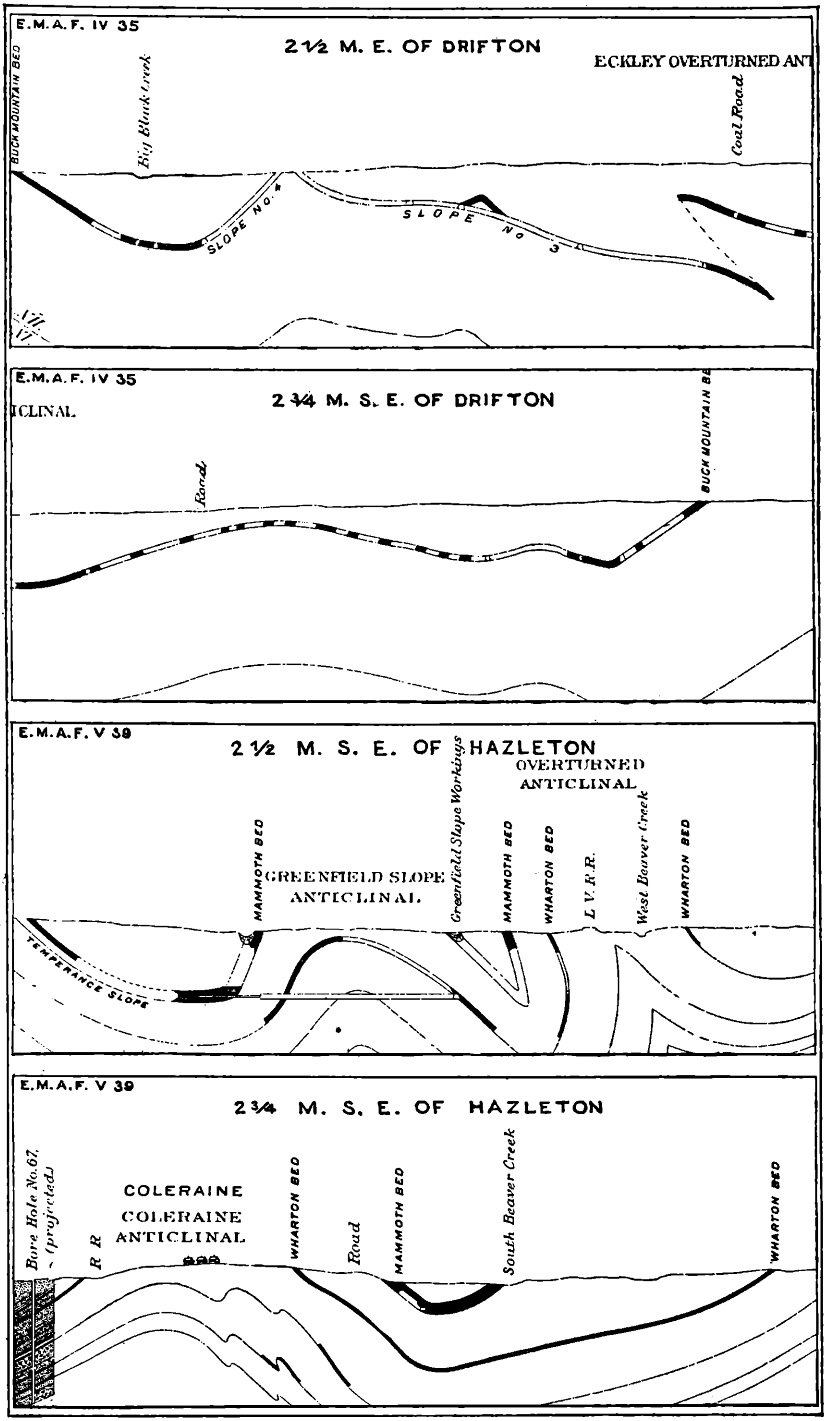

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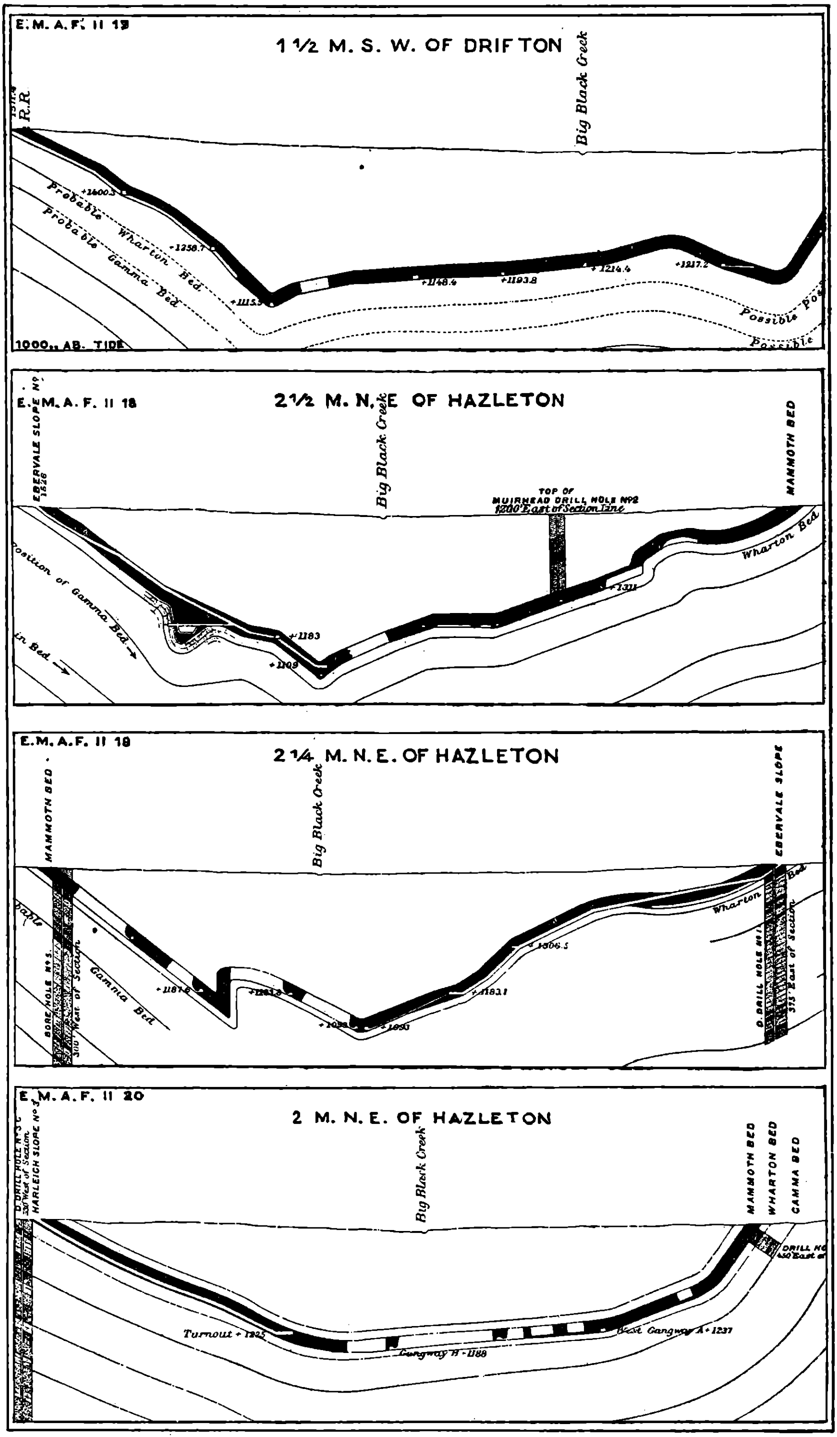

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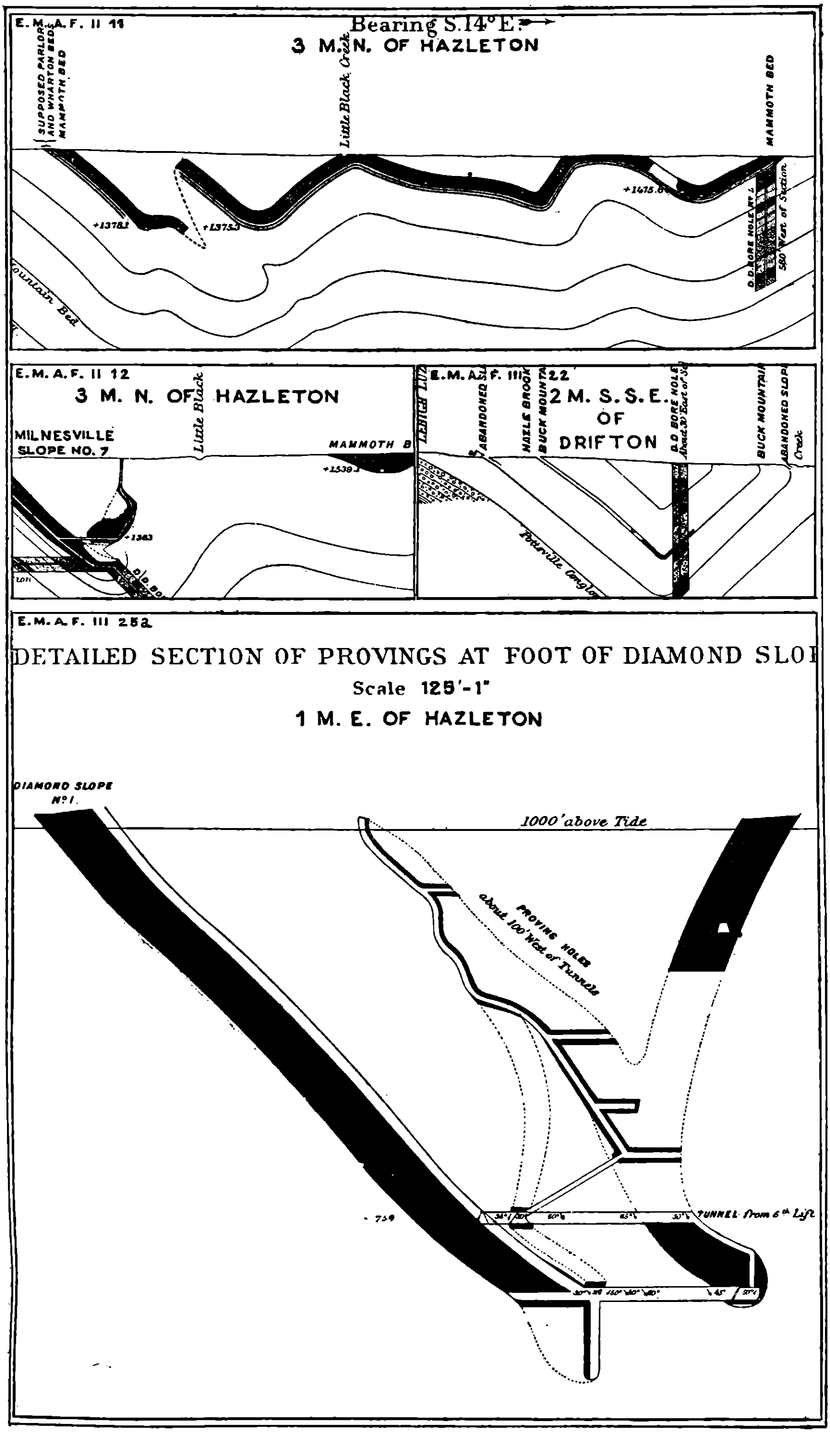

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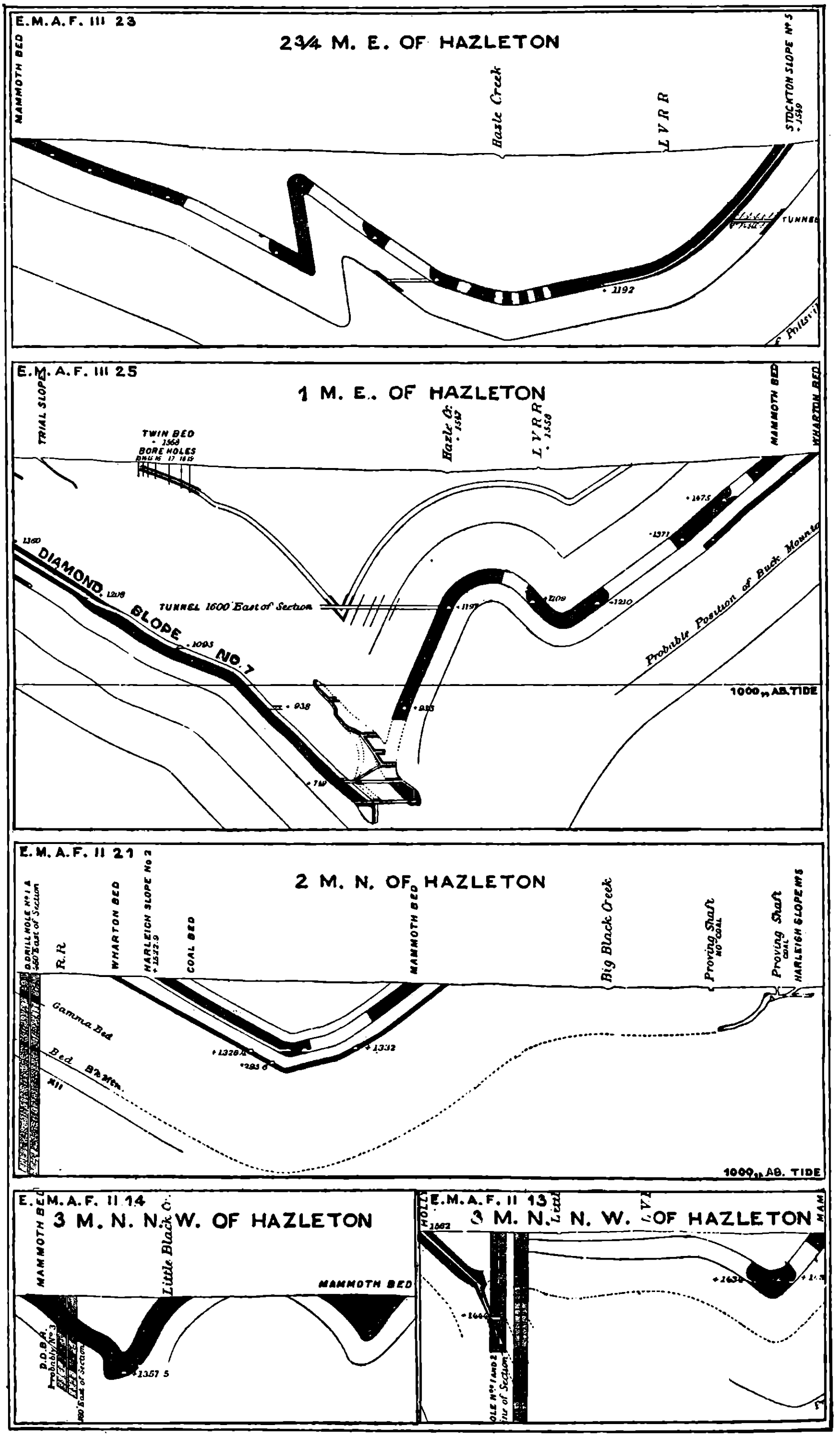
PLATE XIV.



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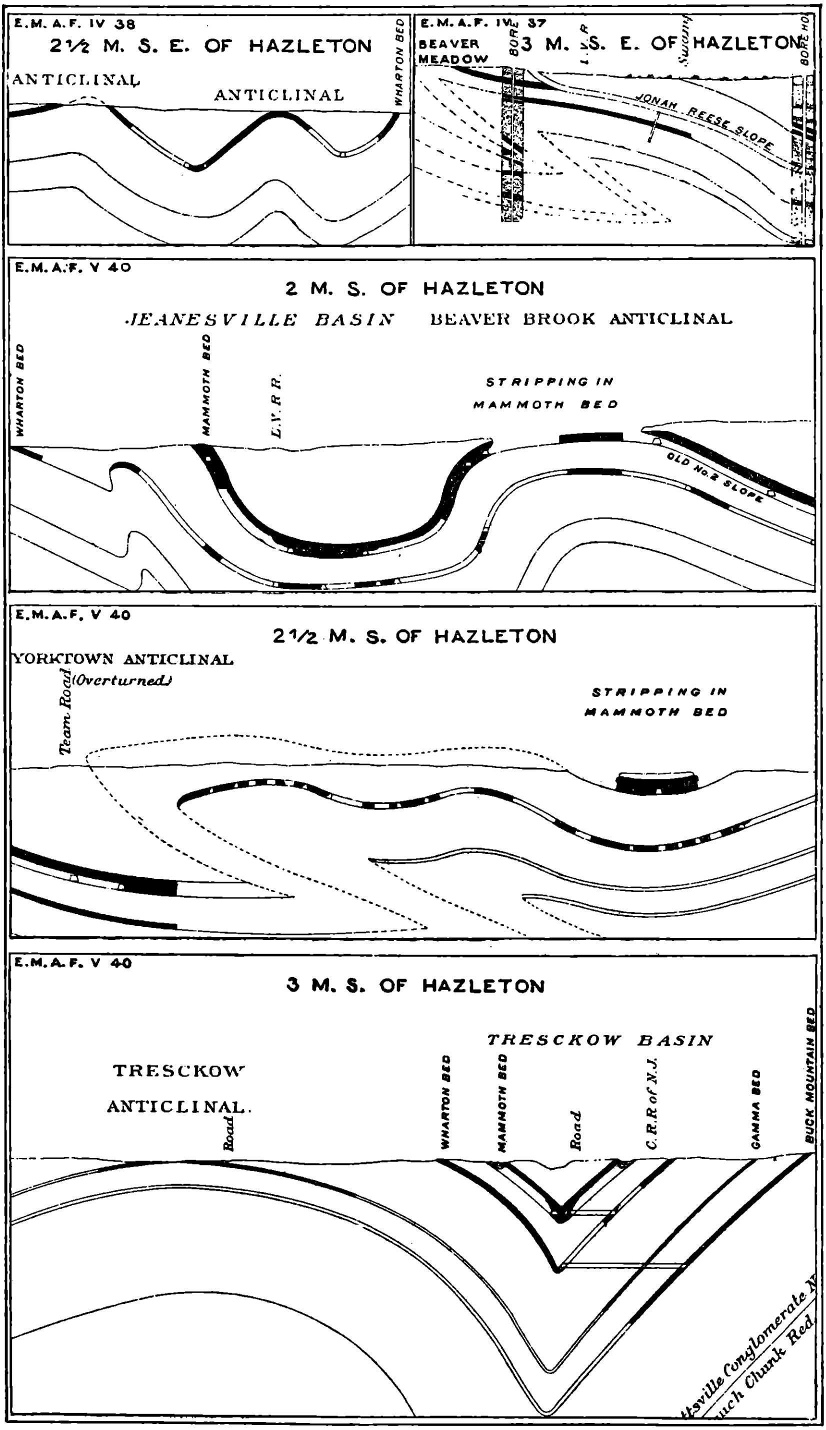

Cross-Sections in the Anthracite-Region.

PLATE XVI.

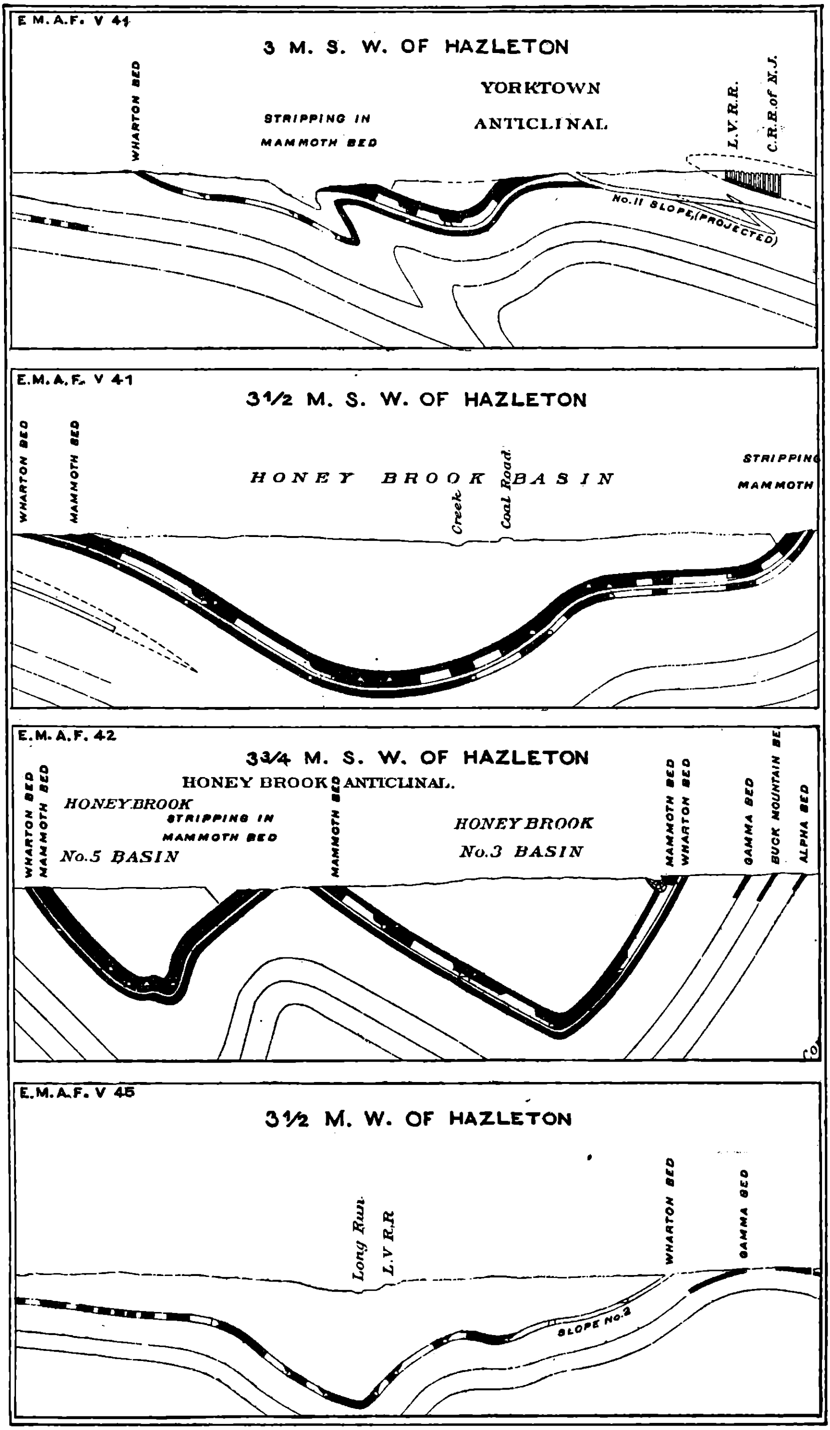

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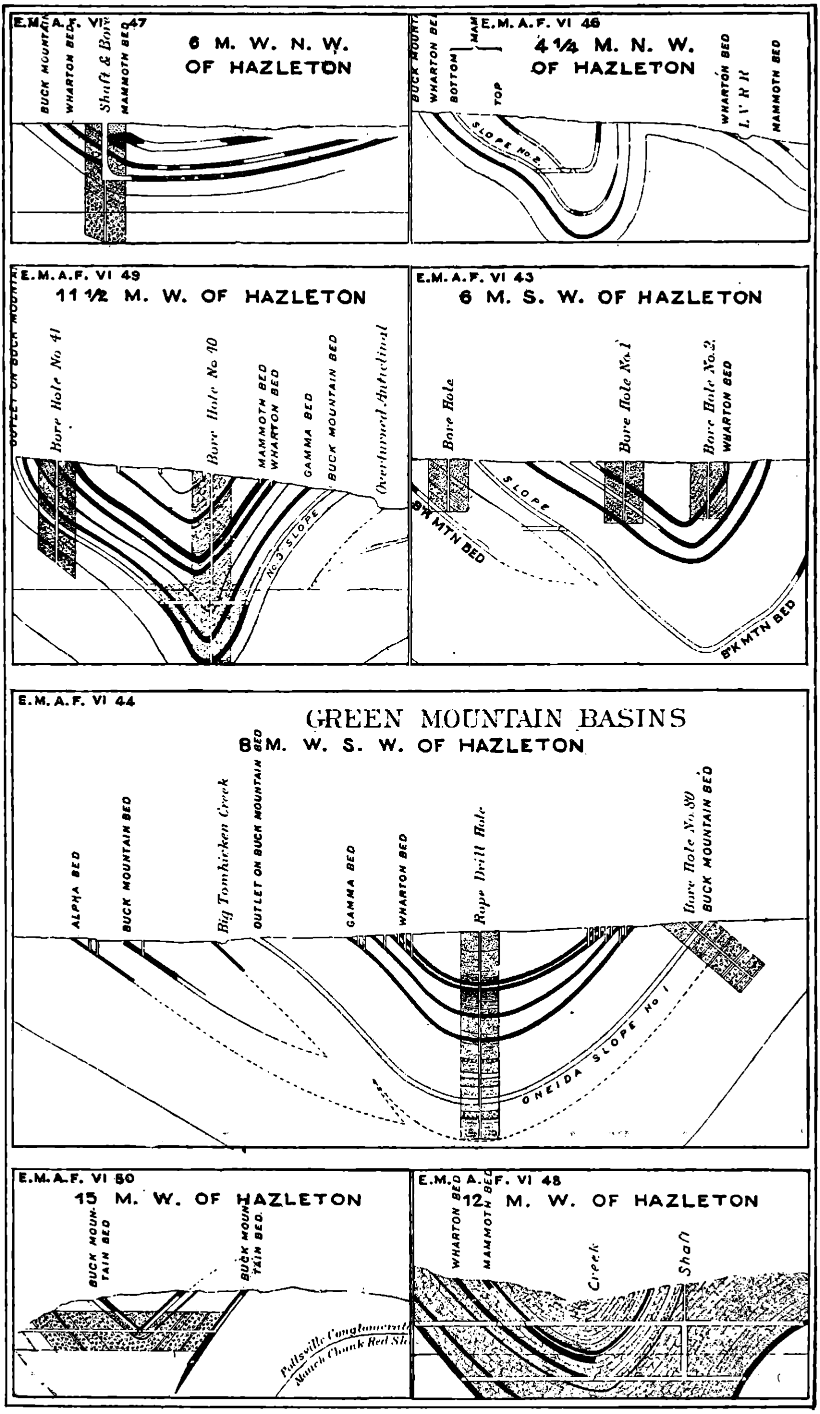
PLATE XVII.



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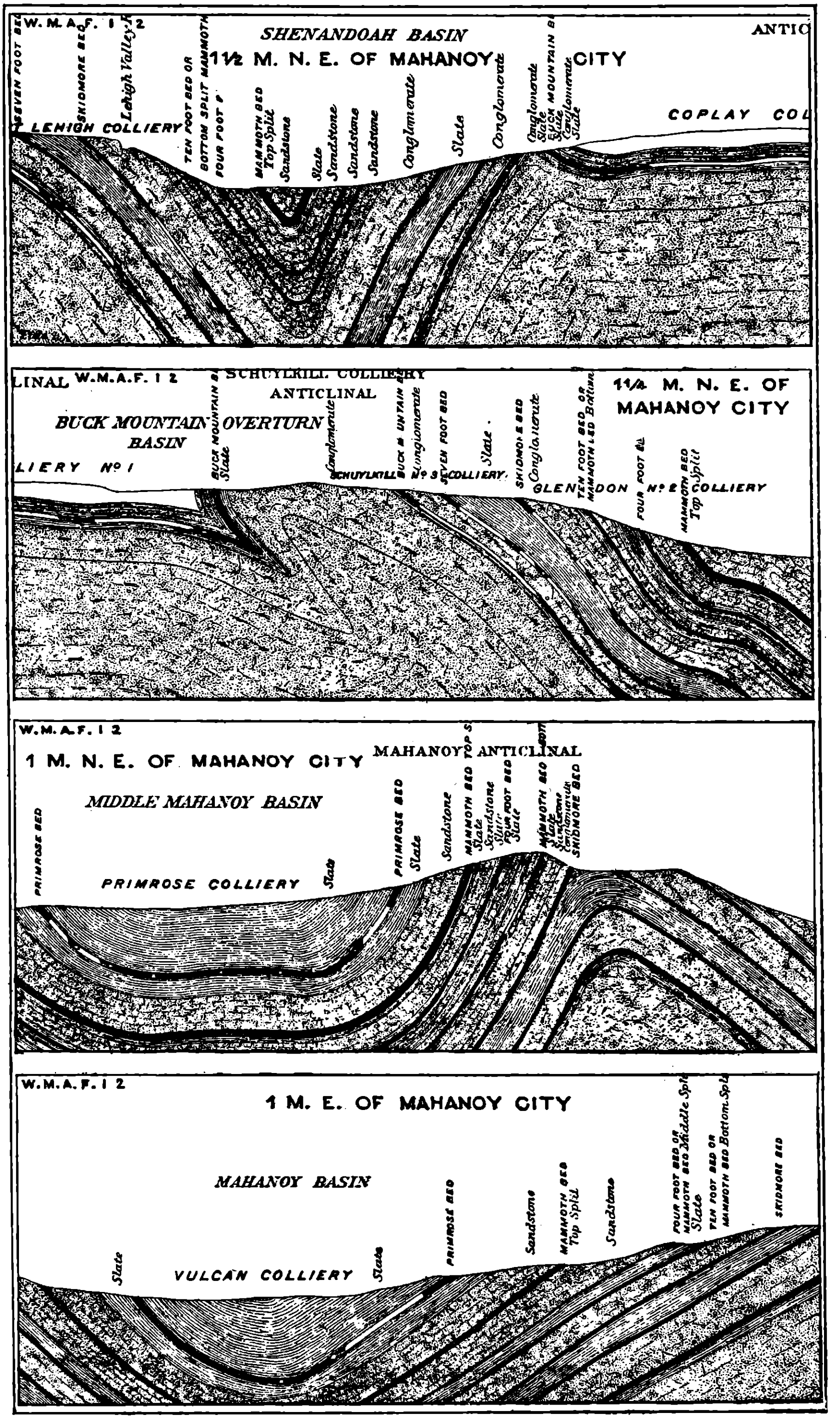

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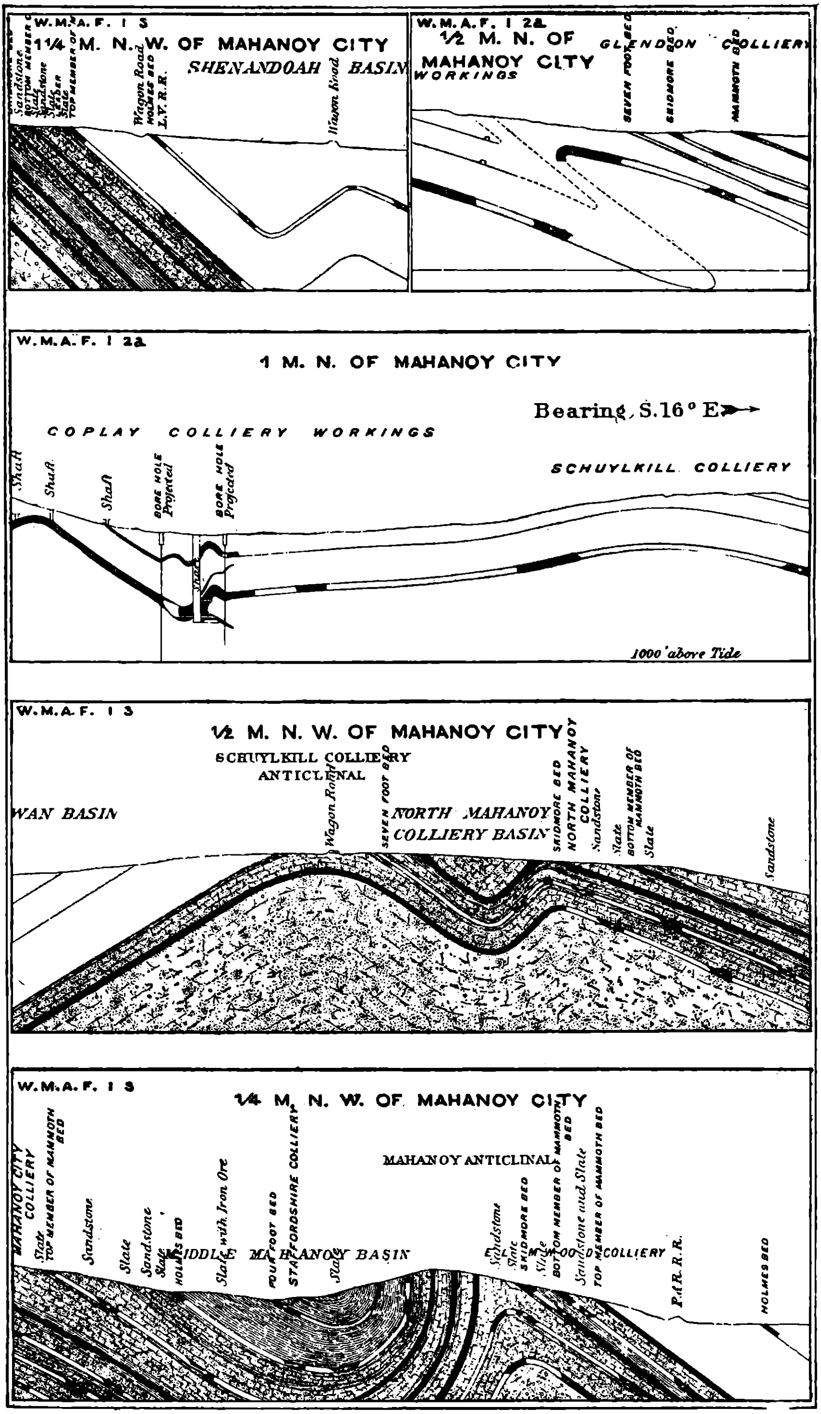
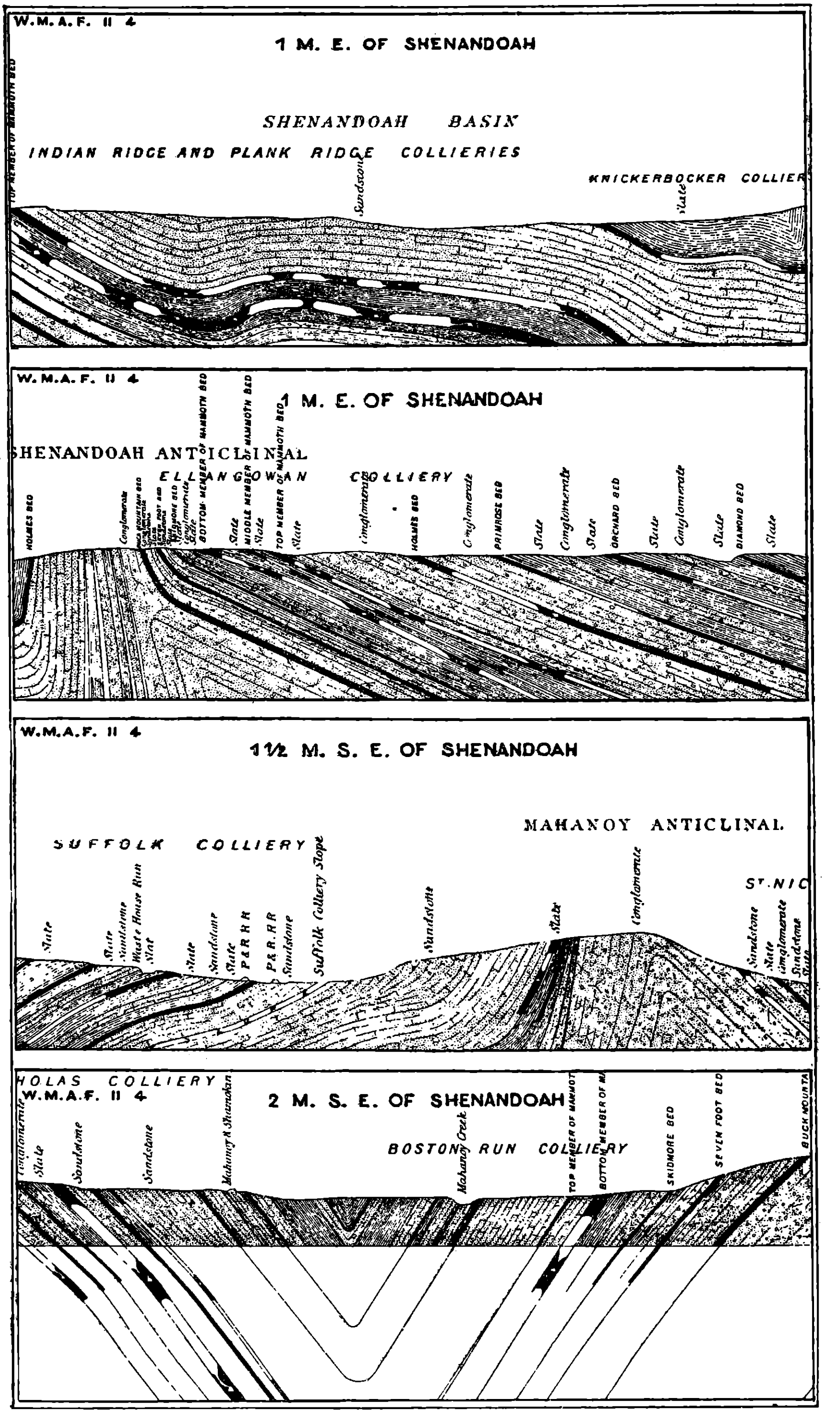


Cross-Sections in the Anthracite-Region.

PLATE XX.



Cross-Sections in the Anthracite-Region.
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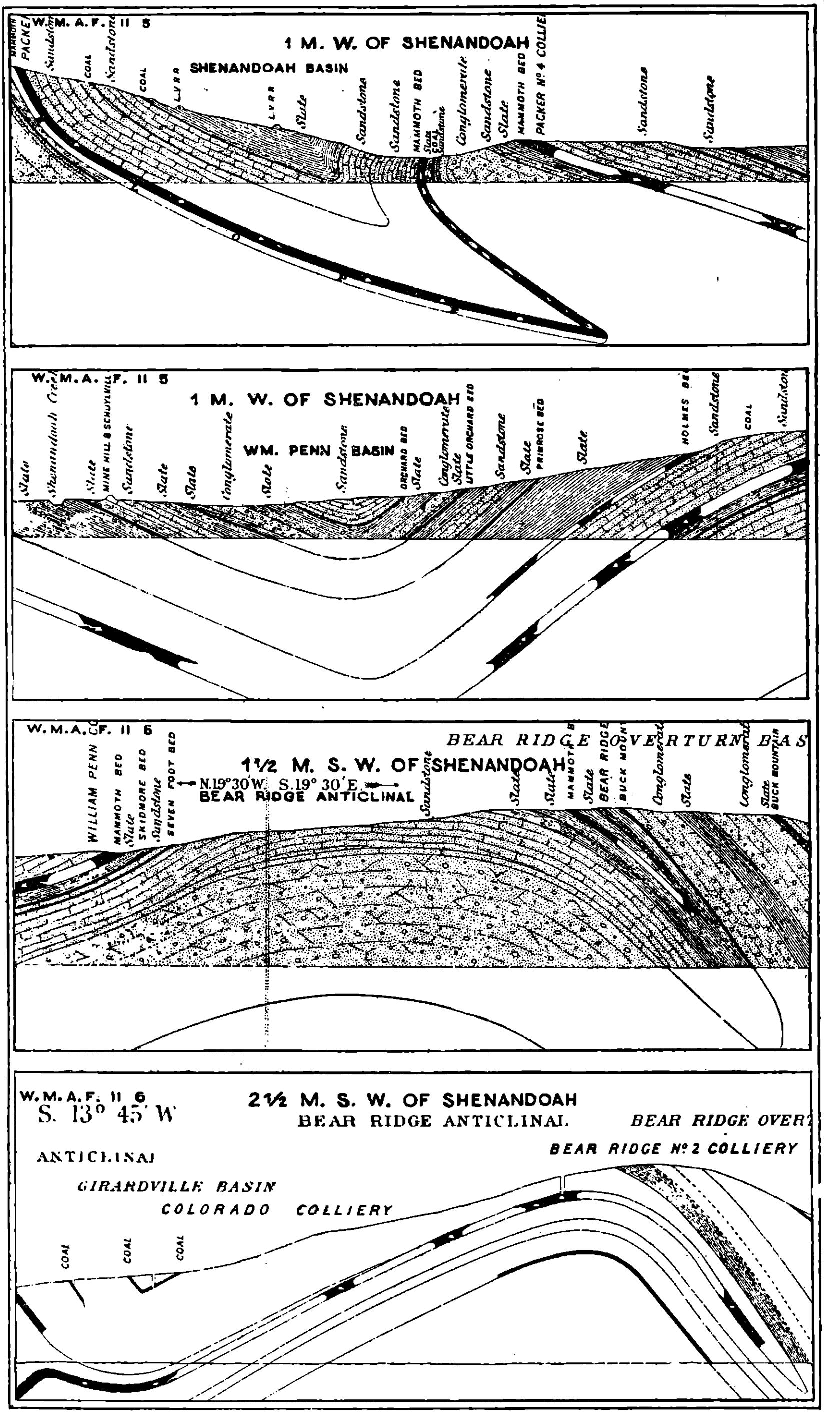
PLATE XXI.



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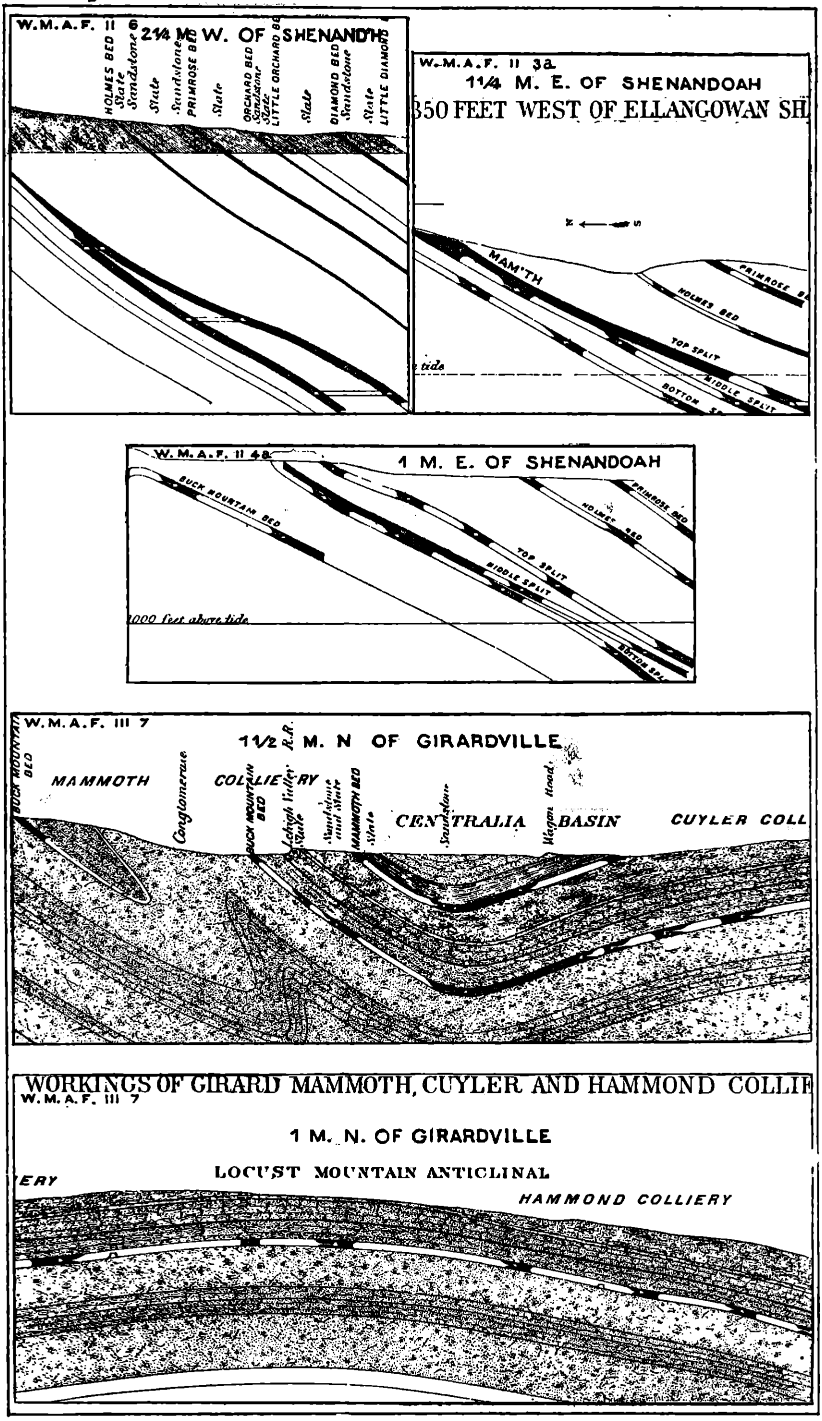

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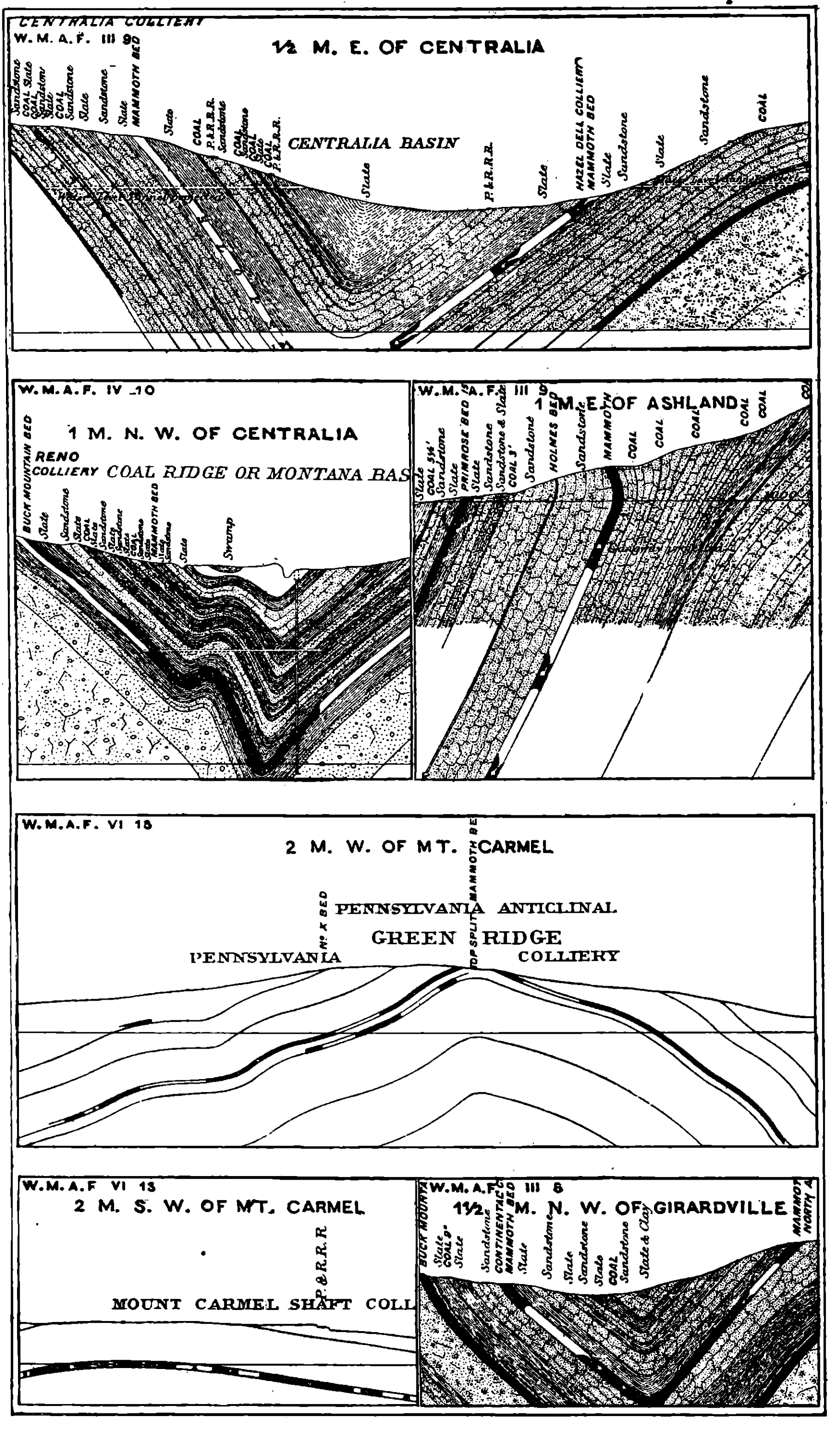

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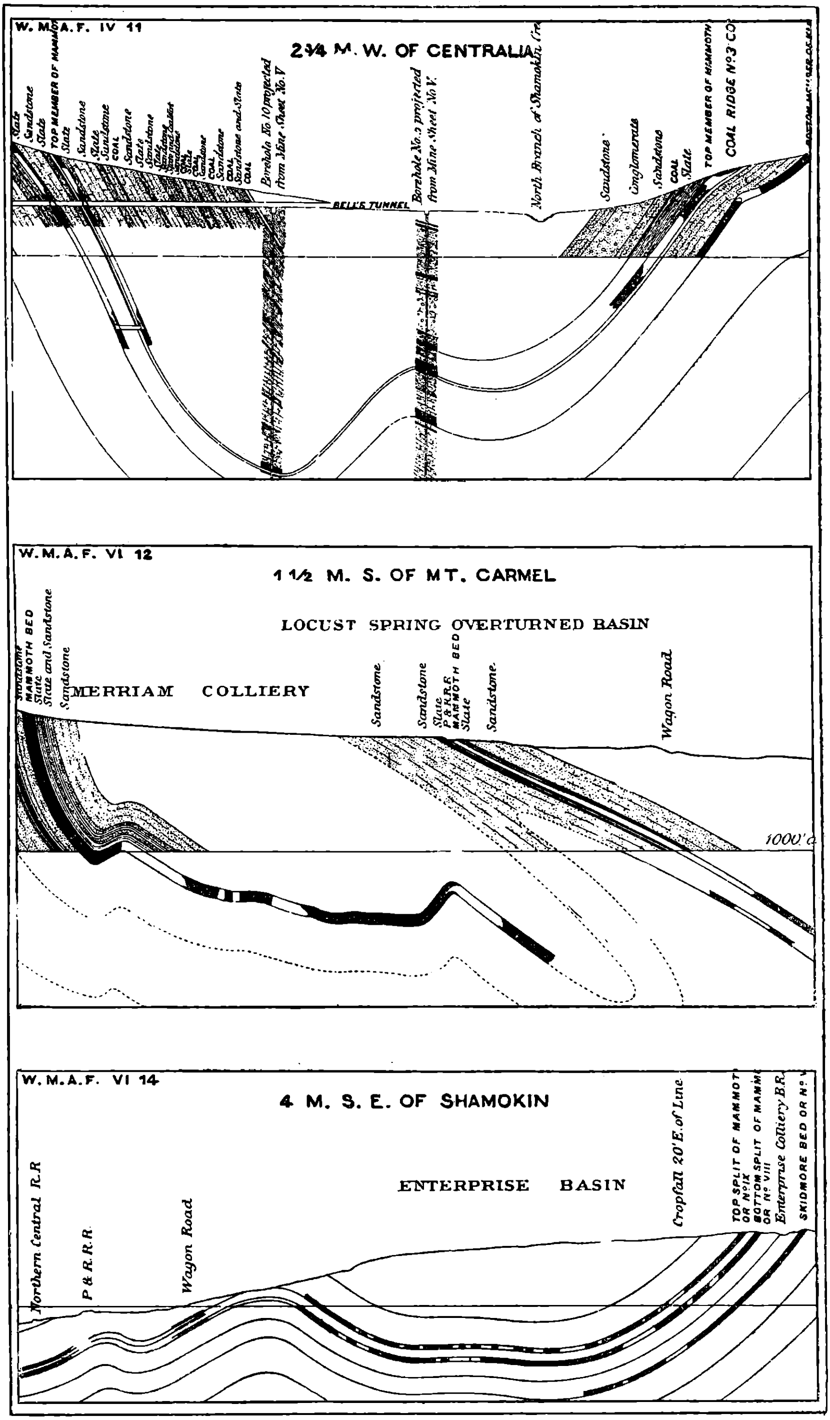

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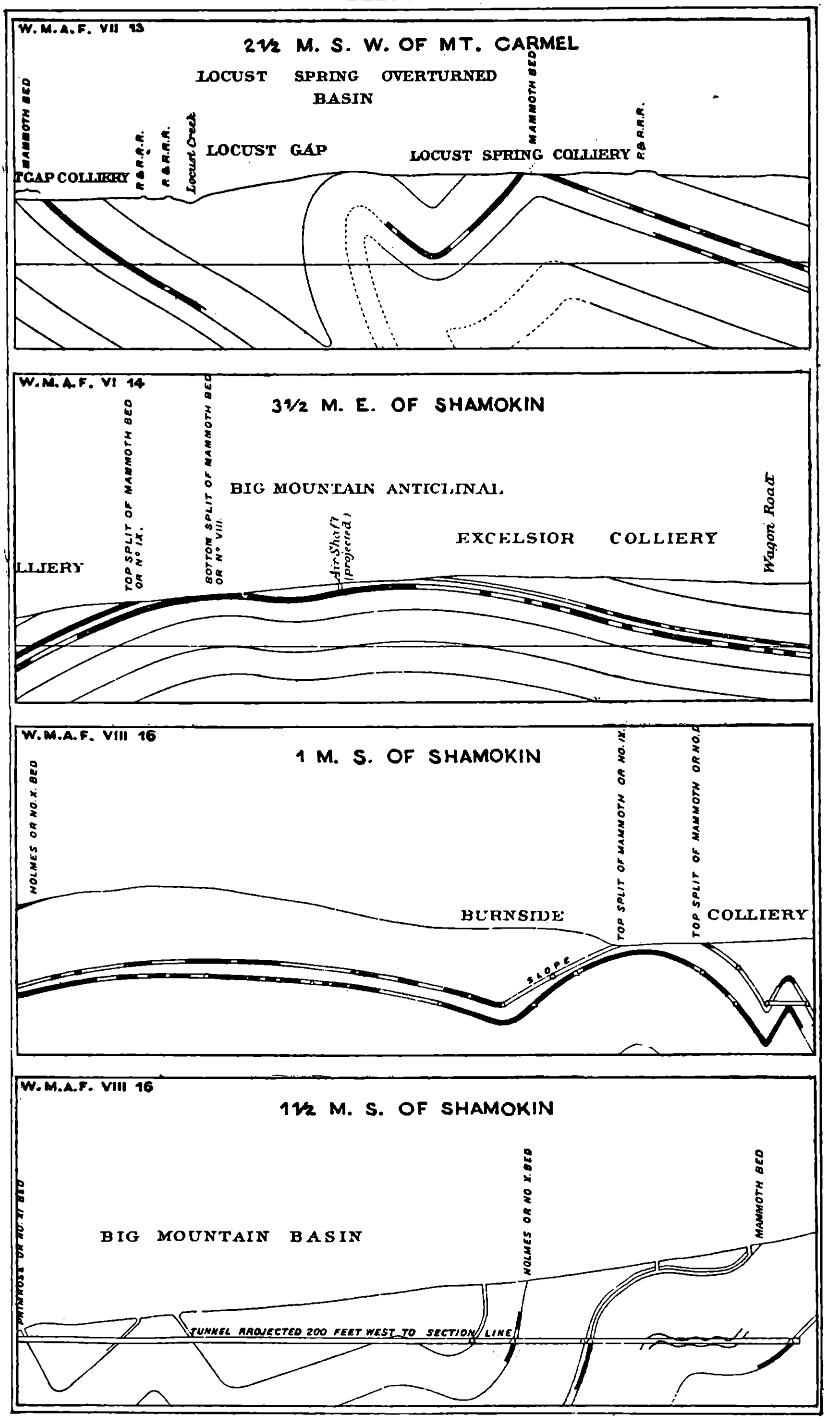

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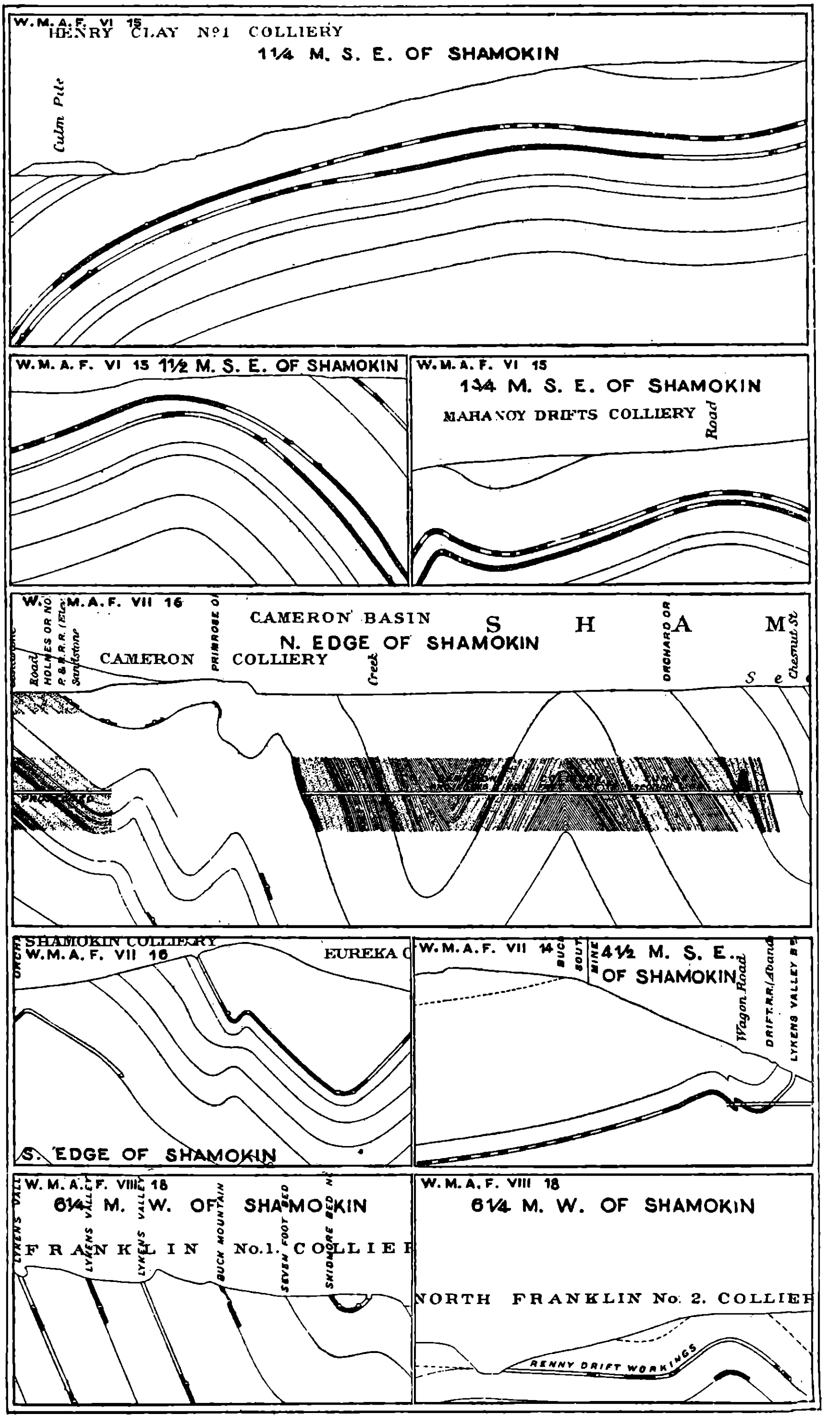

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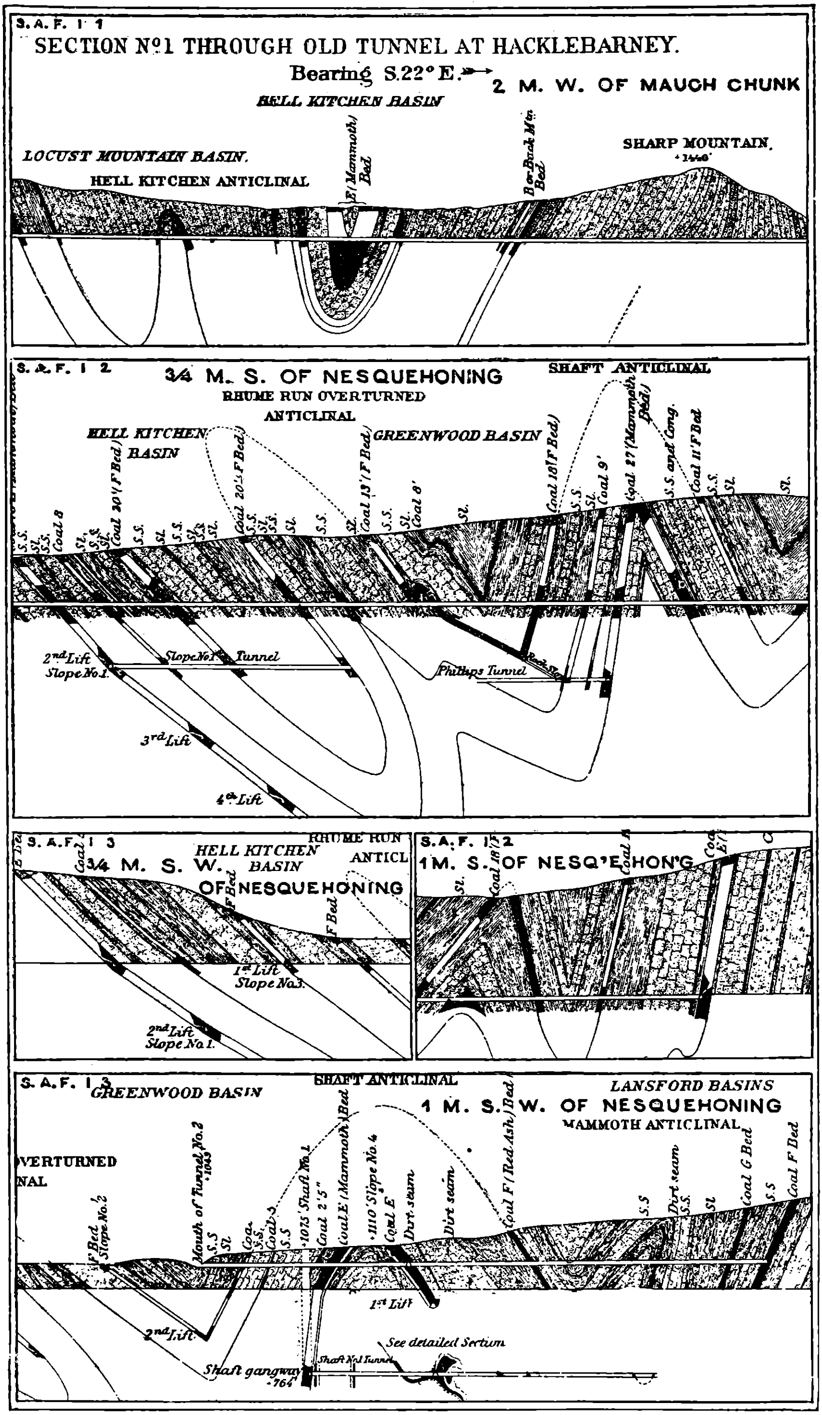

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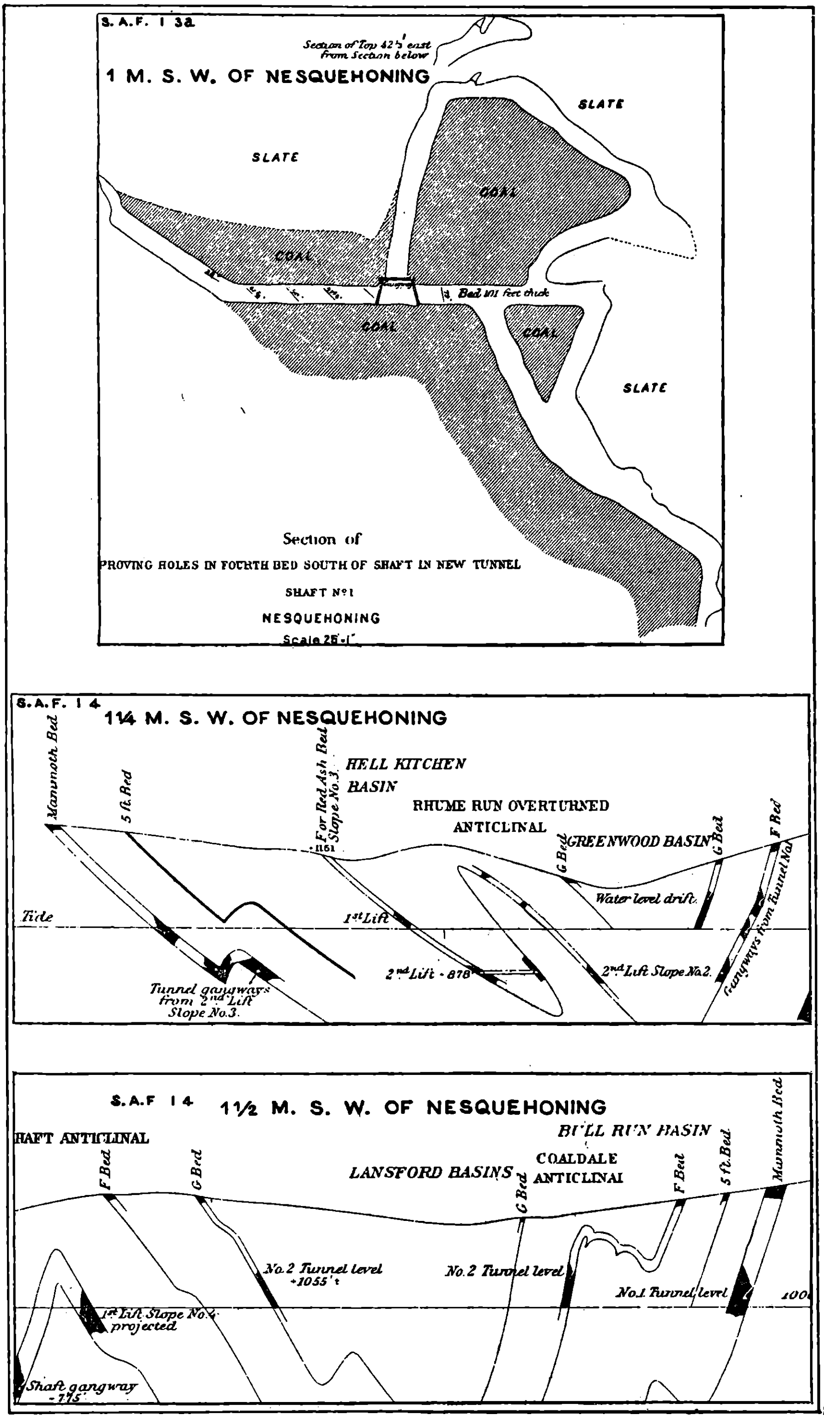

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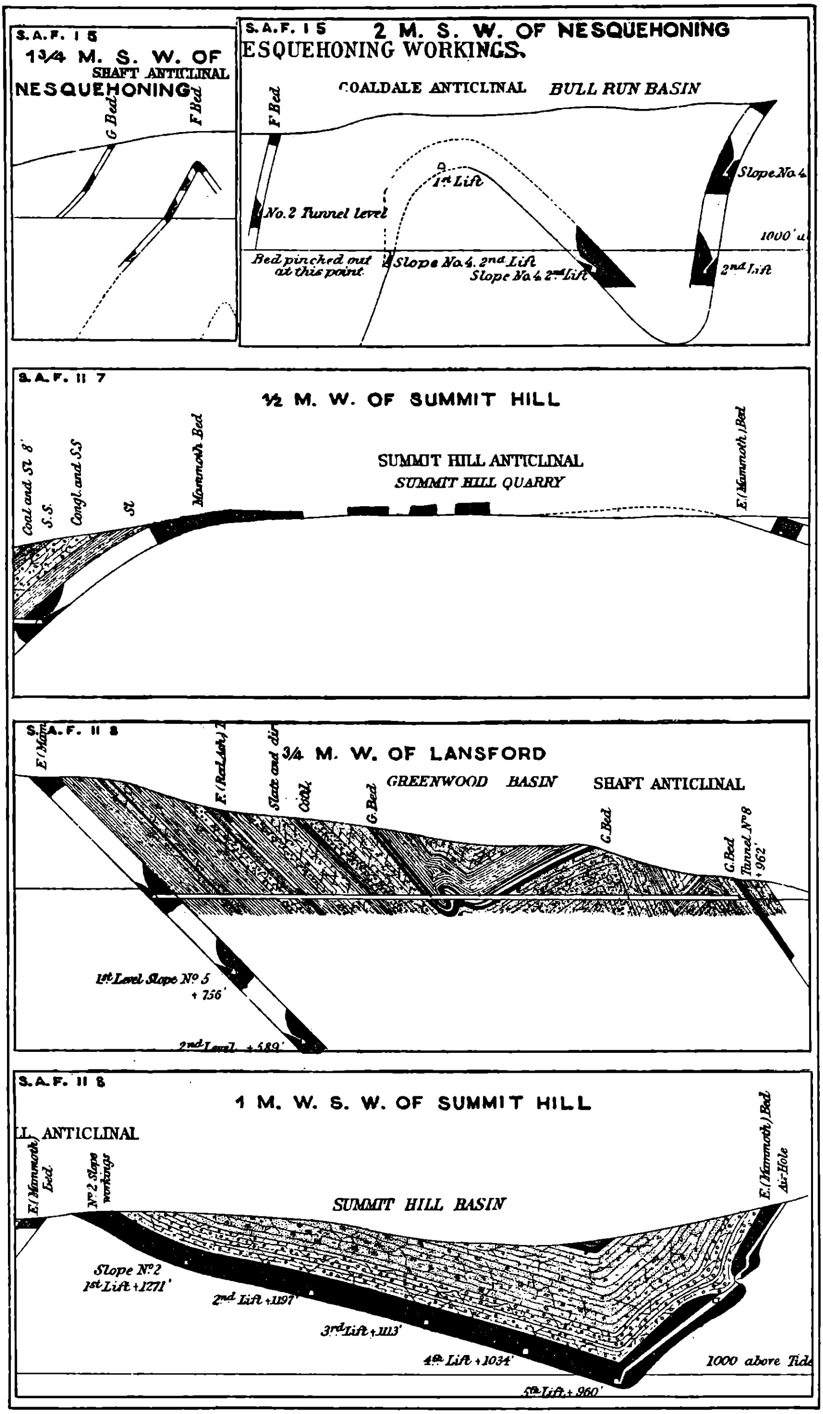
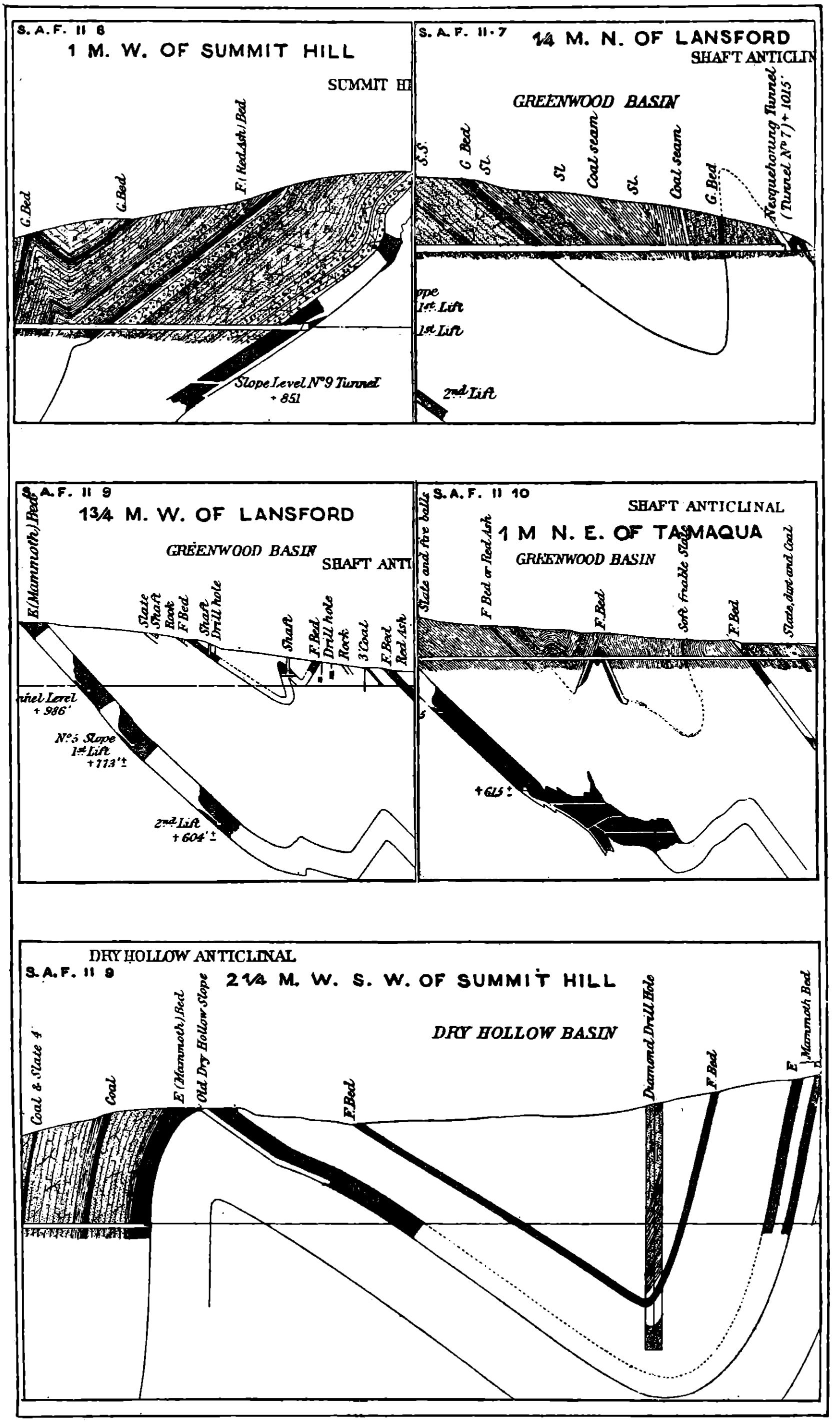


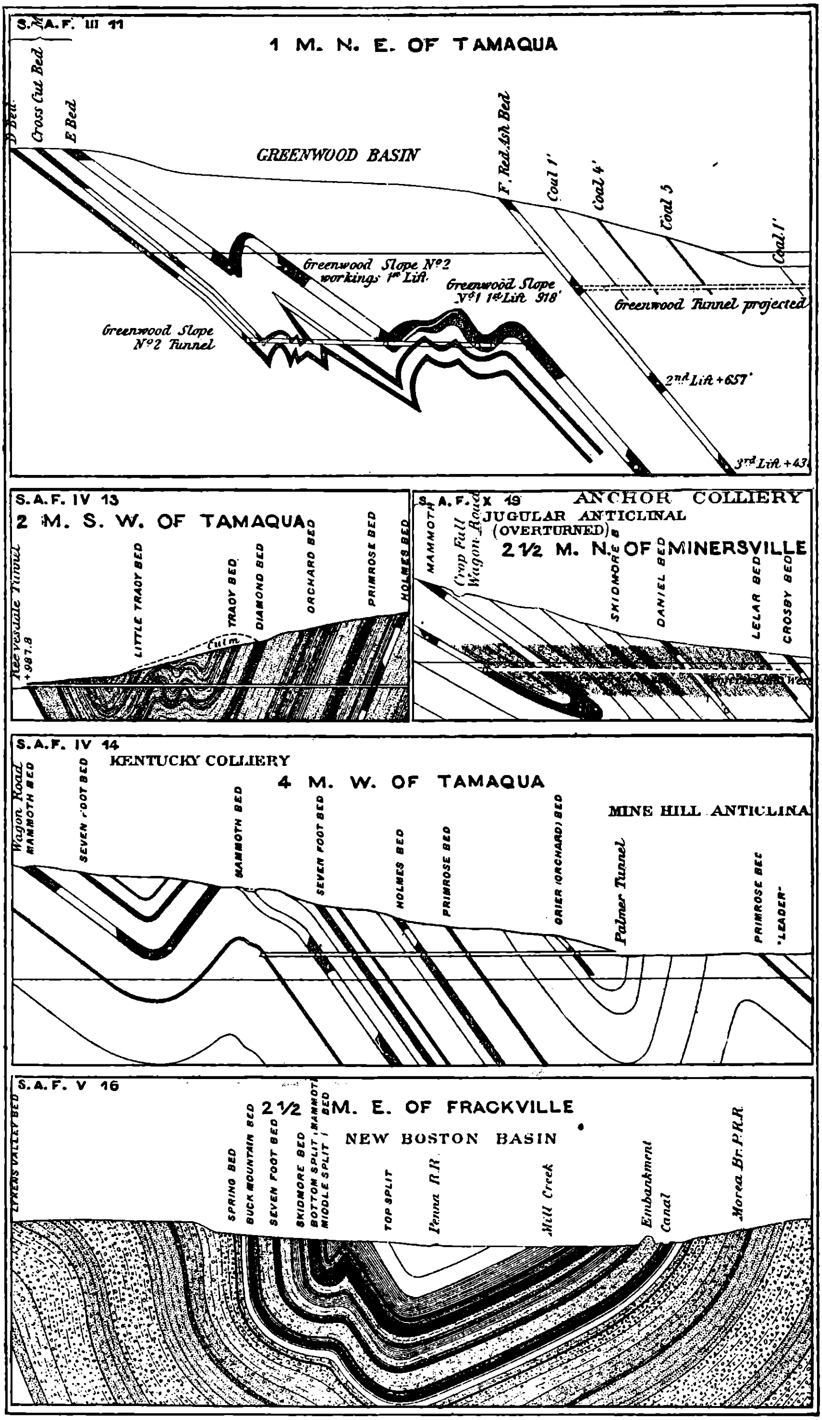
Cross-Sections in the Anthracite-Region.

PLATE XXX.



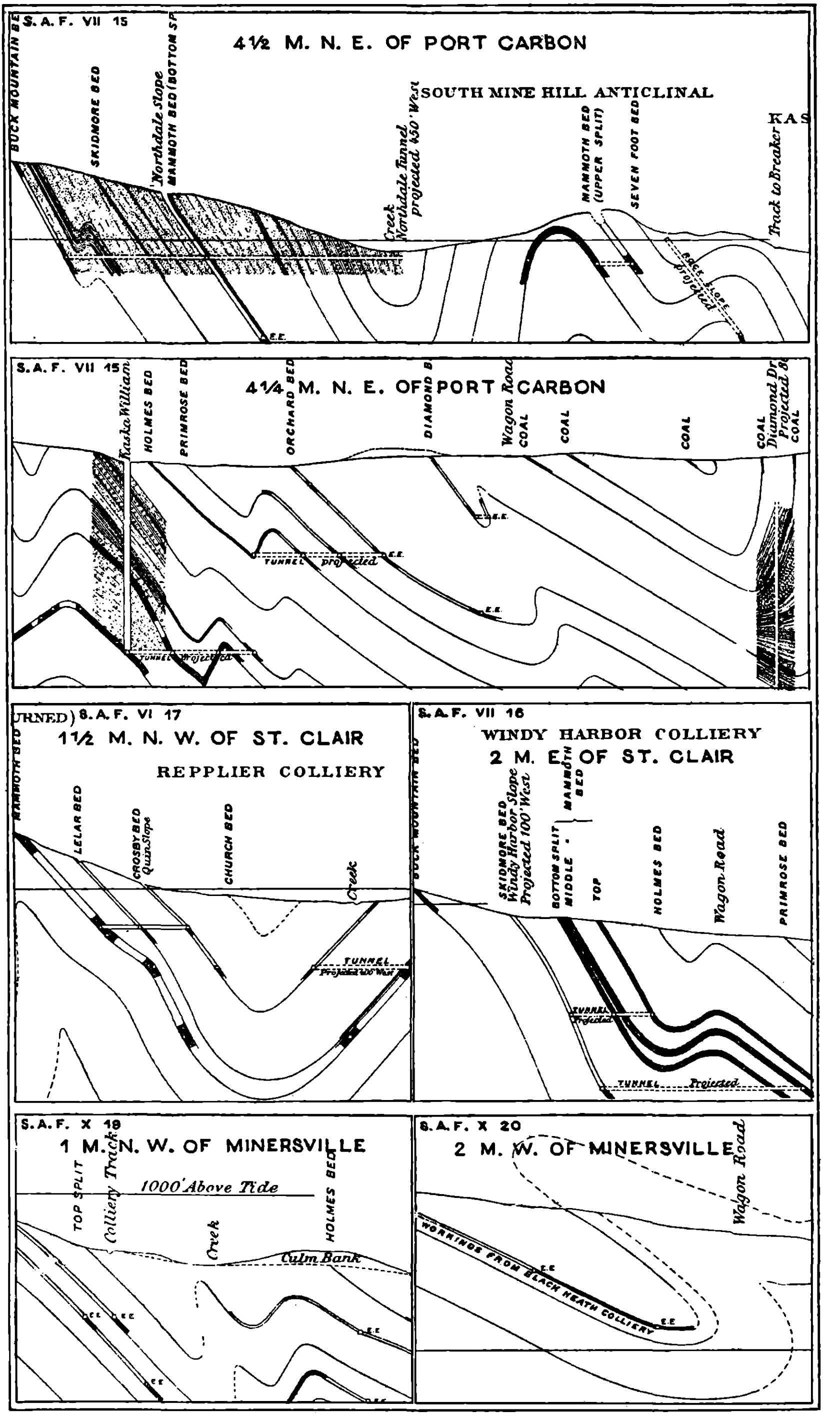
Cross-Sections in the Anthracite Region.

PLATE XXXI.



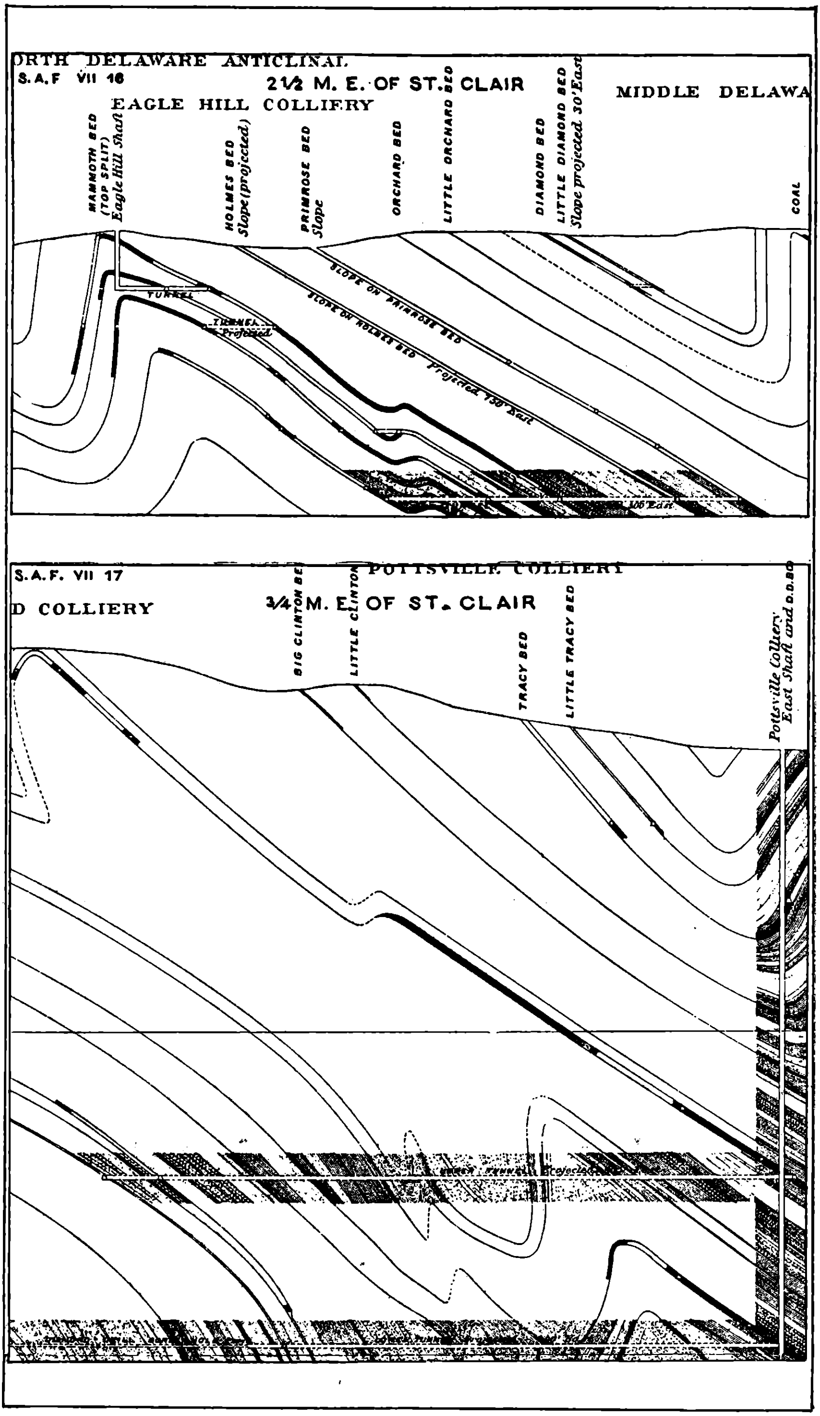
Cross-Sections in the Anthracite-Region.

PLATE XXXII.



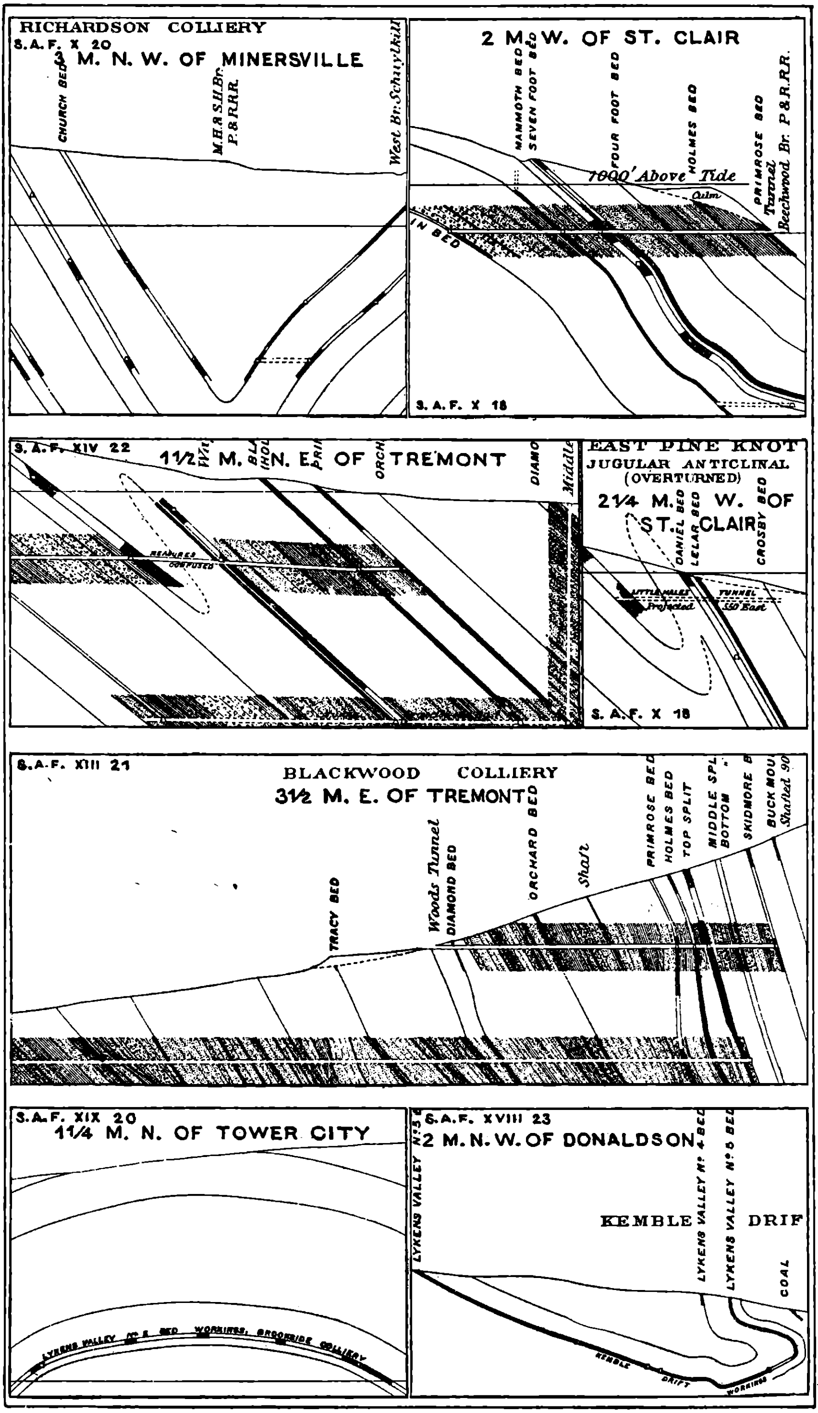
Cross-Sections in the Anthracite-Region.

PLATE XXXIII.



Cross-Sections in the Anthracite-Region.

PLATE XXXIV.



Cross-Sections in the Anthracite-Region.

SUBJECT TO REVISION.

[TRANSACTIONS OF THE AMERICAN INSTITUTE OF MINING ENGINEERS.]

Folds and Faults in Pennsylvania Anthracite Beds.

BY BENJAMIN SMITH LYMAN, PHILADELPHIA, PA.

(Atlanta Meeting, October, 1895.)

POSTSCRIPT.

IN reply to inquiries and comments which have reached me since the publication of this paper, and in explanation of some seeming discrepancies between my statements in the text concerning the amount of displacement of the faults, on one hand, and certain figures in the plates on the other hand, I give here, with some additional remarks, my measurements of the displacements in the different sections, which it originally seemed unnecessary to print:

Plate.	Section.	Feet.	Plate.	Section.	Feet.
II	F	25	VII	1	35
II	20	50	VII	1′	75
III	20	90±	VIII	7	165 ?
IV	28	95	IX	36	100
IV	10	135 ?	X	28	90
IV	12	130	XI	35	370 ??
IV	11	240	XI	39	35
V	19	700 ??	XIII	12	110
V	19	50	XIII	25A	380 ??
V	B	105	XIV	25	380 ??
V	C	35	XIV	13	?
VI	18	35	XV	40	60
VI	18	25	XV	40′	(700)*
VI	B	40	XXVI	14	20
VI	A	10	XXVIII	8	?
VII	18A	20	XXX	10	115 ?
VII	4′	10			

* Overturn.

By displacement, I mean neither the throw, *i.e.*, the vertical distance apart of the two edges of a faulted bed (what Mr. Bailey Willis calls "the vertical throw"), nor the heave (which he calls "the horizontal throw"), *i.e.*, the horizontal distance along the fault from one edge or end of the faulted bed to the other; but the distance along the dip of the fault between the two said edges or ends.

As to the displacements in Plate XI., Section 35, and Plate XIII., Section 25 A, marked 370 and 380 feet, respectively, it seems quite doubtful whether they are really so great. The one on Plate XV., Section 40, which is marked 700 feet, seems to be more properly an overturn (and, in fact, is so drawn), with perhaps a fault of very doubtful extent.

Of the large displacements, there remains only to be considered the one on Plate V., Section 19, marked 700 feet.

In that case, it appears, on the examination of the mapping of the mine-sheet (Northern Coal-Field, Part I., sheet vi.), that, owing to the irregular crumpling of the rock-beds, the section-line at that particular place is, for some distance, nearly parallel with the strike. A section at right angles to the local strike would show a much smaller displacement. The map, however, does not seem to give all the information necessary for a complete section. Perhaps, some of the lines were omitted, on account of the danger of too great confusion in representing workings on the same bed at two different levels. Or, I may fail to understand the lines perfectly because the two sets are not distinguished by dotting or otherwise. Apparently, the displacement would be, at most, less than 250 feet.

The concluding statement of my paper is based on the 26 measurements of displacement which were not affected with very great doubt, excluding those which are doubly marked (??) as doubtful in the foregoing table.

It will be noted that normal faults appear but seldom on the sections of the Pennsylvania Geological Survey. One reason may be, that such faults would be, more or less, nearly parallel to the section-lines. Moreover, their usual small extent would probably render them inconspicuous in small-scale sections.